COGNITIVE-MOTOR INTERFERENCE IN MULTI-TASKING RESEARCH

EDITED BY: Karen Zentgraf, Hermann Müller and Eliot Hazeltine
PUBLISHED IN: Frontiers in Psychology

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88963-170-4
DOI 10.3389/978-2-88963-170-4

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COGNITIVE-MOTOR INTERFERENCE IN MULTI-TASKING RESEARCH

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Citation: Zentgraf, K., Müller, H., Hazeltine, E., eds. (2019). Cognitive-Motor Interference in Multi-Tasking Research. Lausanne: Frontiers Media.
doi: 10.3389/978-2-88963-170-4

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frontiers in Psychology

EDITORIAL
published: 30 July 2019
doi: 10.3389/fpsyg.2019.01744

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Editorial: Cognitive-Motor Interference in Multi-Tasking Research

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Keywords: interference, multi-tasking, costs, movements, real world

OPEN ACCESS

Edited and reviewed by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *15 June 2019*
Accepted: *12 July 2019*
Published: *30 July 2019*

Citation:
Zentgraf K, Müller H and Hazeltine E (2019) Editorial: Cognitive-Motor Interference in Multi-Tasking Research. Front. Psychol. 10:1744. doi: 10.3389/fpsyg.2019.01744

Editorial on the Research Topic

Cognitive-Motor Interference in Multi-Tasking Research

Multitasking is ubiquitous in our everyday life. Accordingly, situations in which two or more tasks need to be handled concurrently or in close temporal succession have been studied intensely. Different paradigms have been developed in that context (Koch et al., 2018). Over the last decades, the psychological refractory period (PRP) paradigm has dominated dual-task research, because it allows quantitative predictions of reaction time increases coupled to stimulus onset asynchrony. Part of the success of this paradigm is grounded in the fact that most of the studies are run under strict experimental control with very elementary tasks, mostly characterized by a definite start and ending. However, it remains unclear whether these limited settings sufficiently reflect the range of eventualities we find in real life. Rather, there is accumulating evidence that important factors modulating multitask performance are not sufficiently captured by the PRP approach. Here we focus on evidence that motor responses that involve continuous interaction with the environment may engage processes that alter the coordination of concurrently performed tasks in fundamental ways.

The studies collected in this Research Topic contribute to this question by showing that:

A) Even basic postural tasks require central processing capacities, potentially competing against concurrent cognitive tasks.
B) Movements in space are related to concepts of location and direction, thereby emphasizing aspects of spatial compatibility and embodied contingencies.
C) Multitasking performance is not driven strictly by the set of stimuli and responses but rather depends on task representation within the subject.
D) In cases in which postural control is required, task prioritization becomes a crucial factor. Irrespective of instruction, priority is given to tasks with larger costs of failure. Several studies presented here confirm that this effect is more pronounced in elderly persons.
E) Although priority is often given to motor tasks, they still demonstrate dual-task interference. Surprisingly, there are also cases of a "dual-task benefit."
F) The concept of "automaticity" must be (re)considered as a potential explanation for variations in dual-task costs.
G) Motor behavior is generally not temporally discrete but evolves over time. The ability to predict changes in processing demands allows the control system to appropriately allocate resources.
H) Dual-task settings push the control system to its limits, which makes them particularly useful to study control in clinical populations.

The study by Stelzel et al. nicely demonstrates aspect (A). Individual differences in dual-task performance in a motor-cognitive task can be explained by different degrees of involvement of the lateral prefrontal cortex, a region thought to play an important role in central resource allocation.

Aspect (B) is addressed by Stephan et al. Switch costs, mixing costs, and congruency effects are typically preserved under different postural demands. However, the authors observed an increased congruency effect when standing compared to sitting.

The study of Halvorson and Hazeltine links aspects (B) and (C). Previous studies have shown that dual-task costs are largely reduced when stimulus and response modalities are compatible within each task and separate across tasks. The authors show that this is not sufficient for the reduction of dual-task costs but that dual-task costs depend on the relationship between the tasks.

Also relating to aspect (C), Hosang et al. did not observe any modulation of the PRP-effect by hand-proximity to stimuli. The authors interpret this observation as confirmation that the bottleneck is in a central processing stage, which is not affected by peripheral (embodied) contingencies.

In line with (C), Schumacher et al. demonstrate that dual-task effects are not strictly linked to the sheer number of stimuli and responses on a given trial but critically depend on whether the task is represented as single task or dual task.

Aspect (D) emphasizes that task prioritization depends on the nature of the motor output. According to the "posture first" hypothesis (Lindenberger et al., 2000), postural tasks like balancing, walking, or running receive priority for processing resources due to the large costs of failure. Because costs of failure are higher in older subjects, their resource allocation is even more biased.

This is nicely supported by the study of Wechsler et al. Older subjects keep larger safety margins in a virtual driving scenario than younger participants. This effect is amplified under dual-task conditions, particularly when the secondary task requires visual attention.

However, Janouch et al. demonstrate that this "costly-task-first" effect is not pervasive. As expected, in an ecologically more valid street crossing scenario, dual-task costs increased with age. However, task prioritization did not follow a general "posture first" principle. Furthermore, dual-task costs were not consistently larger for visual than for auditory versions of the loading task. The priority given to each task appears to be specific to the circumstances.

This specificity is confirmed in a study with children by Schott and Klotzbier. They observe an interaction between task demands with age and discuss these findings in light of a resource model that assumes that allocation regimes and executive function resources differ across age groups.

Kiss et al. did not find any signs of dual-task costs when combining a cognitive task (counting) and a motor task (balancing), providing a link between aspects (C) and (E). Furthermore, single-task practice only improves the practiced task, whereas dual-task training improves both tasks. This finding is taken as an indicator for no or very small overlap in processing for the tasks.

Lüder et al. also use a cognitive-motor paradigm and demonstrate that task prioritization may change with age (D). In their study, children show performance decrements in standing and walking when a calculation task is added (E). These costs are reduced similarly by single and dual-task training.

But even the movements of experts (i.e., athletes) demonstrate that posture is not always preserved from performance decrement in case of cognitive-motor task interference. Fleddermann and Zentgraf show that jumping performance of elite volleyball players show clear decrements when jumping was linked to a game-specific, visually presented decision task (E).

However, performing a motor and a cognitive task in parallel does not necessary lead to impairments (dual-task costs) in all relevant performance measures (F). Langhanns and Müller demonstrate that the frequency of repetitive movements sometimes increases when a cognitive task is performed concurrently. However, this seems to be limited to motor tasks that are under automatic control.

In these cases, processing load may be considerably reduced, partly because events are predictable (G). Accordingly, Broeker et al. show that processing in multitasking is altered depending on the degree of predictability of events. Prediction of the time course of events allows for the preplanned allocation of processing resources, to prepare for upcoming trials but also for error processing and updating the contents of memory. It is argued that these predictive processes are automatic but also depend on task characteristics and explicit cues.

Ewolds et al. combined a go/no-go auditory RT task with a motor tracking task to reveal differences in processing load when the tracking task was partly predictable. Differences in predictability might be induced by either implicit or explicit knowledge about regularities in the target trajectory. Even though the effects of implicit/explicit predictability are visible in motor performance, dual-task costs are small and therefore not a major target of this manipulation.

Besides these contributions to deepening our understanding of cognitive control, studying multitasking might also contribute to addressing diagnostic problems in clinical contexts (G). McIsaac et al. point to the fact that dual-task costs are indicative of limitations in processing capacities in healthy individuals and thus may be exacerbated in neurodegenerative patients. This group of persons may benefit strongly if specific dual-task-impairments could be addressed by specific interventions.

This Research Topic develops new areas in multitasking research and attempts to evolve the field with respect to traditional concepts. We have proposed theoretical and empirical challenges that these new and traditional paradigms present to multitasking research. In this editorial, we provide a brief inventory of the papers in the Research Topic and outline promising avenues for future research. Specifically, we highlight the role of the motor components of responses and how these components are embedded within a task context in determining the pattern of dual-task costs. Understanding these factors is essential for generating models of dual-task performance that translate to real-world situations.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

ACKNOWLEDGMENTS

We thank all the authors for their contributions.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 29 March 2019
doi: 10.3389/fpsyg.2019.00711

Separation of Tasks Into Distinct Domains, Not Set-Level Compatibility, Minimizes Dual-Task Interference

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Dual-task costs are often significantly reduced or eliminated when both tasks use compatible stimulus-response (S-R) pairs. Either by design or unintentionally, S-R pairs used in dual-task experiments that produce small dual-task costs typically have two properties that may reduce dual-task interference. One property is that they are easy to keep separate; specifically, one task is often visual-spatial and contains little verbal information and the other task is primarily auditory-verbal and has no significant spatial component. The other property is that the two sets of S-R pairs are often compatible at the set-level; specifically, the collection of stimuli for each task is strongly related to the collection of responses for that task, even if there is no direct correspondence between the individual items in the sets. In this paper, we directly test which of these two properties is driving the absence of large dual-task costs. We used stimuli (images of hands and auditory words) that when previously been paired with responses (button presses and vocal utterances) produced minimal dual-task costs, but we manipulated the shape of the hands in the images and the auditory words. If set-level compatibility is driving efficient performance, then these changes should not affect dual-task costs. However, we found large changes in the dual-task costs depending on the specific stimuli and responses. We conclude that set-level compatibility is not sufficient to minimize dual-task costs. We connect these findings to divisions within the working memory system and discuss implications for understanding dual-task performance more broadly.

Keywords: dual-task performance, ideomotor theory, set-level compatibility, perfect time-sharing, modality compatibility

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *10 March 2018*
Accepted: *14 March 2019*
Published: *29 March 2019*

Citation:
Halvorson KM and Hazeltine E (2019) Separation of Tasks Into Distinct Domains, Not Set-Level Compatibility, Minimizes Dual-Task Interference. Front. Psychol. 10:711. doi: 10.3389/fpsyg.2019.00711

INTRODUCTION

Doing two things at the same time typically gives rise to performance impairments, known in laboratory settings as dual-task costs. Dual-task costs are observed across a wide range of tasks composed of different S-R rules (e.g., Pashler, 1994; Liepelt et al., 2011; Halvorson et al., 2013); however, some pairs of tasks give rise to smaller costs than other pairs. One factor believed to affect the magnitude of dual-task costs is the modalities of the stimuli and responses used for each task (e.g., Hazeltine et al., 2006).

One theory that can help account for the effects of input- and output-modalities on dual-task costs is Ideomotor (IM) theory (Greenwald, 1972). IM theory proposes that actions are encoded in the form of representations that include the sensory feedback (e.g., a visual image or acoustic signal) associated with the environmental outcome of that response, called response codes[1] as well as the motor commands required to make a response. When the stimulus cuing the action matches the environmental outcome of the action, the response code can be directly activated and response selection is highly efficient (Greenwald and Shulman, 1973). Thus, IM theory predicts minimal dual-task costs when the stimuli are identical to, or very closely resemble, the environmental outcomes of the required responses. As a result of this similarity, there is a significant amount of overlap between the stimulus and the response, causing the response selection process to be highly efficient for both tasks (Greenwald and Shulman, 1973). In these cases, there is no evidence of dual-task interference. For example, a verbal shadowing task in which participants must say the letter "A" in response to hearing the letter "A" should produce little dual-task costs when paired with another task. Because, according to IM theory, representations of actions include their expected consequences, a stimulus similar to the outcome of an action will directly activate a portion of its response code, facilitating selection so that central operations that would otherwise be required by both tasks can be avoided. By "directly," it is implied that the desired response can be activated without the intervention of central operations that typically serve as a bottleneck during dual-task performance (Greenwald, 1972).

Although IM theory provides a straightforward account of the role of modalities in dual-task costs[2], experimental findings have been difficult to explain using only IM theory. Previous findings of little or no dual-task costs with IM-compatible tasks have only been observed when *both* tasks are IM-compatible (Greenwald and Shulman, 1973; Greenwald, 2003, 2004, 2005; Halvorson et al., 2013). This is hard to explain with IM theory, because if the response code for one task is directly activated when its stimulus corresponds with the environmental outcome, then it is unclear why the response code for the other task must also be directly activated to avoid costs. The direct activation of response codes for one of the tasks should be sufficient.

Therefore, Halvorson et al. (2013) proposed an alternative explanation for findings of minimal dual-task interference. Drawing heavily on Wickens et al. (1983), the authors proposed that dual-task costs were minimal because one task was purely spatial and the other task was purely verbal. According to this spatial-verbal hypothesis, the lack of overlap across all components of the two tasks (including the specific input- and output-modalities as well as central codes) by the IM-compatible tasks reduces crosstalk such that the two tasks can be kept sufficiently separate.

As a direct test of the new hypothesis, Halvorson and Hazeltine (2015) pitted the spatial-verbal hypothesis against the IM hypothesis by changing the mappings within each task such that both tasks maintained optimal modality pairings but some of the individual mappings of the S-R pairs were IM compatible and some were less compatible. Participants performed one of two visual-manual (VM) tasks and one of two auditory-vocal (AV) tasks in a between-subjects 2 × 2 design. For the VM tasks, the stimuli were static images of hands making finger presses and the responses were the corresponding finger presses. The two versions of the VM task differed in the mappings between the stimuli and responses so that there was an IM-compatible task where participants made the keypress that corresponded to the image and an incompatible task where participants made the opposite movement (e.g., pressed a key with their index finger when they saw the image of the hand pressing the key with the middle finger). Similarly, for the AV tasks, the stimuli were auditory presentations of the words "Cat" and "Dog" and the responses were the spoken words "Cat" and "Dog." The only difference between the two versions of the task was the mapping. In the IM-compatible AV task, participants repeated the word they heard and in the opposite task they said the other word (e.g., said "Dog" when they heard "Cat"). Unsurprisingly, two IM-compatible tasks produced little evidence of dual-task costs. Surprisingly, when one or even both tasks had opposite mappings, single-task RTs were slowed but there were still no dual-task costs. This unexpected finding is difficult to reconcile with an element-level direct activation theory. It is not possible that the same stimulus (e.g., an image of a hand with the index finger bent down in the position of having just pressed a button) can directly activate the response code for the index finger in one group and the middle finger in the other.

Halvorson and Hazeltine (2015) proposed that the spatial-verbal hypothesis, which predicts dual-task interference will be avoided when the S-R pairs for each task can be kept sufficiently separate, can account for these findings. Specifically, the VM tasks in their experiments used S-R mappings that relied exclusively on spatial information and the AV task used S-R mappings that relied exclusively on verbal information [similar to the proposal by Wickens' (1984)]. Despite the fact that only some of the mappings between individual elements in the tasks were IM compatible, the separability of the two tasks into distinct processing domains allows for highly efficient dual-task performance in all conditions (Halvorson and Hazeltine, 2015).

An alternative explanation for the minimal dual-task costs observed with the IM-compatible and opposite mappings from Halvorson and Hazeltine (2015) can be constructed on the

[1]Greenwald and Shulman (1973, p.1) define a response code (or "an image of its sensory feedback") as "the precise form in which information must occur to enable selection of a given response. In terms of IM theory, the response code is directly activated by signals that closely resemble sensory feedback from the response. A relationship between stimulus and response of IM compatibility is defined, then, as one in which the stimulus resembles sensory feedback from the response." It is our interpretation of IM theory that response codes include both internal and external feedback produced by the response. Research on IM-compatibility and dual-task interference has primarily focused on manipulating the relationship between the external feedback from the environmental outcome and the stimulus used to signal the action but it is possible that internal feedback may also play a role in the formation and subsequent activation of the response code.

[2]We are testing a limited combination of modalities (specifically those involved in the visual-manual and auditory-vocal task pairings) to address questions that have arisen from a literature that has primarily considered these modality pairings. It is possible that other modalities are involved in the representations activated by visual and auditory stimuli, but distinguishing the various components of the representations is beyond the scope of this study.

basis of findings from motor control studies on typing tasks. According to Martin et al. (1996), typing does not require a unique program for each keypress; instead, a general motor program can be used to execute multiple individual keystrokes. The visual stimuli used in the opposite tasks from Halvorson and Hazeltine (2015) may have utilized motor codes that resembled those used for typing tasks in which case a generic code could have been activated that allowed participants to retrieve much of the necessary information to make a response (see e.g., Lee et al., 2016). The small changes to the motor program required to make a specific response could have been completed on each trial without incurring significant dual-task costs. This possibility provides further support for developing a new VM task using images of hands that are not in a position that resembles the view of one's hands during the real-world act of typing.

Set-Level Compatibility

The findings of Halvorson and Hazeltine (2015) are inconsistent with explanations that depend on individual stimuli directly activating individual response codes, as in IM theory (Greenwald and Shulman, 1973). However, there is a direct activation explanation that could explain such findings: the dual-task costs in previous IM experiments may have been greatly reduced because of *set-level* compatibility rather than *element-level* compatibility (Fitts, 1954; Fitts and Deininger, 1954; Kornblum et al., 1990; Huestegge and Hazeltine, 2011). Set-level compatibility is based on the amount of correspondence between the set of items that make up the stimulus and response pairs for each task (see Kornblum et al., 1990). The manipulation in Halvorson and Hazeltine (2015) only affected element-level compatibility, so set-level compatibility was constant for all conditions. The VM stimuli and response sets were set-level compatible because images of hands and manual responses are strongly related. Likewise, auditory words are compatible with vocal responses. Thus, it could be that set-level compatibility allowed for the negligible dual-task costs.

The original claim by Greenwald and Shulman (1973) was that the compatibility driving the reduced dual-task costs was dependent on the relationship between the specific features of the individual items of each S-R pair in the task pairing. Each stimulus item was assumed to directly activate its unique response, thereby dramatically reducing the amount of shared central resources required for response selection. An alternative account is that this direct activation occurs as a result of compatibility at the set-level rather than element-level, with the images of the hands activating both hand responses and the words activate the vocal responses. While this form of activation may be insufficient to select the appropriate single response, it may be adequate to resolve the appropriate response set and reduce cross-talk between the tasks.

Current Experiment

To address whether separability of the tasks based on stimulus-response (S-R) mappings (as suggested by the spatial-verbal hypothesis) or the correspondence within the task pairings at the set-level is responsible for the near-elimination of dual-task costs observed in Halvorson and Hazeltine (2015), we used an identical design but with novel stimuli (see **Figure 1**). The novel visual stimuli were static images of hands, like those used in Halvorson and Hazeltine (2015), but they did not depict keypresses. Rather, they were intentionally designed to avoid having a direct spatial relationship with the correct response. We term the resulting VM tasks "paramotor" (PM) tasks, because although the stimuli do not mimic the sensory consequences of the appropriate response as in IM tasks, they do share perceptual features with the appropriate response modality such that the correct response set is strongly signaled by stimuli.

In the PM VM task participants pressed the 1 key to a picture of a hand with the fingers in the shape of a "V" and the 2 key to the hand in the shape of a "W" (see **Figure 1**)[3]. We alluded to the similarities between the formation of the fingers in each image and the English letters "V" and "W" as a way to describe the difference in the images for the purposes of selecting the correct response. We do not make any strong assumptions that the images of the hands were interpreted as or treated the same as visual presentations of actual letters. Importantly, the PM stimuli are visually similar to the IM stimuli, in that both sets depicted a right hand from roughly the same point of view as if the subject was looking down on their own right hand. To ensure that they could not easily be coded via spatial codes (which would only be a further test of the element-level hypothesis) verbal labels were introduced in the instructions to differentiate the stimuli. Although these labels were used to describe the stimuli to the participants, they were not necessary for selecting or executing

[3]The letter scheme described in the instructions was used to provide a verbal means for distinguishing between the two visual stimuli. We did not include a description of the thumbs nor was the position of the thumbs consistent with the letter scheme. This did not present difficulties or result in confusion for participants. They were all able to understand the instructions and successfully perform the task.

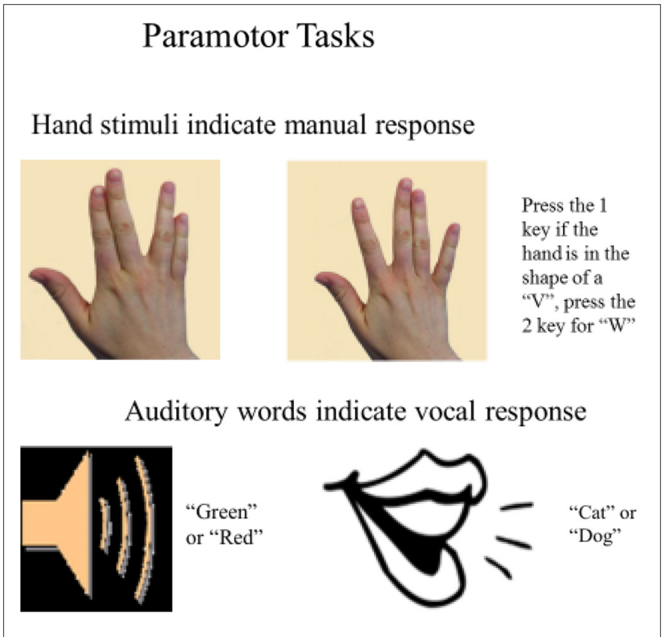

FIGURE 1 | Paramotor stimulus-response sets.

the correct response. In an analogous fashion, we also altered the AV task in which the responses were simple, monosyllabic words mapped to the same stimuli that were used in the IM-compatible task. As in the PM VM task, in the PM AV task the items in the S-R pairs shared some perceptual features but there was not a clear relationship between a specific stimulus and response within the set. In the PM AV task, the vocal responses "cat" and "dog" were randomly assigned to the auditory stimuli "green" and "red." In sum, the PM tasks used in the current experiment were highly similar and were mapped to the same responses as the IM tasks used in Halvorson and Hazeltine (2015). The changes were introduced to test whether compatibility with the responses at the set level (e.g., pictures of hands and spoken words) but not at the element level would facilitate highly efficient dual-task performance.

With these conditions, we test the set-level and spatial-verbal hypotheses. According to the set-level hypothesis, all four pairings should produce a highly similar pattern of small dual-task costs because all tasks use images of hands to directly activate manual response sets and auditory words to activate vocal response sets. In contrast, according the spatial-verbal hypothesis, greater dual-task interference should be observed for the conditions involving the PM tasks than the IM tasks. Specifically, the spatial-verbal hypothesis predicts that reduced spatial correspondence between the stimuli and the left and right manual responses should increase dual-task costs because the VM task can no longer be completed using spatial codes. A similar pattern of results is predicted when the PM AV task is paired with the IM VM task. Presumably, changing the words in the AV task to color words will reduce the extent to which the AV task can be contained in an entirely verbal domain. Thus, the current experiment aims to directly test these hypotheses by examining dual-task costs under conditions in which the set-level compatibility remains constant but the extent to which the tasks can be completed using exclusively verbal and exclusively spatial information differs.

MATERIALS AND METHODS

Participants

Seventy-six undergraduates from the University of Iowa (ages 19 – 25; 37 male, 23 female) were recruited to participate in this experiment. Sixteen participants with overall accuracies of less than 85% were eliminated from the analyses. For the remaining 60 participants, handedness data was collected for two of the three groups (34 right handed, 6 left handed); handedness data was not collected for the PM IM group. All individuals participated in partial fulfillment of a requirement for an introductory psychology course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

Stimuli were presented on a PC computer using the Microsoft Office Visual Basic speech recognition software that also recorded vocal response time (RT) as in Halvorson and Hazeltine (2015). Auditory stimuli were presented through the earphones on a headset which was also equipped with a microphone that recorded the vocal responses. The auditory stimuli were sound files of the words of a female voice saying the word "cat" and "dog" or "red" and "green" depending on the task. These files were taken from an internet database. All auditory stimuli lasted 250 ms and were mapped to the vocal responses "cat" and "dog." In the PM AV task the mappings were arbitrary and counterbalanced across conditions. The visual stimuli were images of hands (**Figure 2**) presented in the center of the screen within approximately 6.7° horizontal by 6.6° vertical neutral colored rectangle on a black background. The stimuli were mapped to manual responses on the 1 and 2 keys on the number pad. The number pad was on a standard keyboard placed on the desk in front of the monitor; participants were allowed to move to a comfortable position and were instructed to respond with the index and middle finger of the right hand; for the PM task mappings were arbitrary and counterbalanced to the same response keys on the same hands across subjects. The visual stimuli were presented on a 19" color LCD monitor that was located approximately 60 cm from the participant.

Design and Data Analysis

We used a 2 × 2 design (**Figure 2**) in which compatibility (IM and PM) was manipulated across both task types (AV and VM). The IM compatible tasks (vocal and manual-shadowing tasks) were identical to those used in previous studies (see e.g., Halvorson et al., 2013; Halvorson and Hazeltine, 2015). All four groups used the same response keys. One cell of the 2 × 2, the cell consisting of two IM compatible tasks, was conducted by Halvorson and Hazeltine (2015) and the data from those 20 participants will be reported again here for comparison.

The design for this experiment consisted of 16 total blocks of trials. Each block type was completed four times. There were 48 trials per block. The first of each block type was considered practice and eliminated from the final analyses, yielding 576 total trials per participant. Participants were given feedback at the end of each block as to the percent of correct responses made and the average RT for each task. All participants in all four groups completed 16 total blocks of trials.

We used the same three block-types as in previous experiments (e.g., Tombu and Jolicoeur, 2004; Halvorson et al., 2013; Halvorson and Hazeltine, 2015): single-task blocks were homogenous, only one task was presented for the entire block; mixed-task blocks (OR blocks) consisted of single-task trials in which the task was randomly selected on each trial but only one task was presented at a time; dual-task blocks required two responses on each trial (AND blocks). To characterize the different types of interactions between concurrently active tasks, we compared differences in RT between OR and single-task blocks (mixing costs) and differences in RT between AND and OR blocks (dual-task costs). We also address the issue reported in previous dual-task studies that arises when participants intentionally or unintentionally prioritize responding to one task over the other (e.g., Levy and Pashler, 2001; Logan and Gordon, 2001). In that case, dual-task costs are sometimes observed in RT s to one task but not the other (Tombu and Jolicoeur, 2004). Because we are interested in the overall effect of responding to

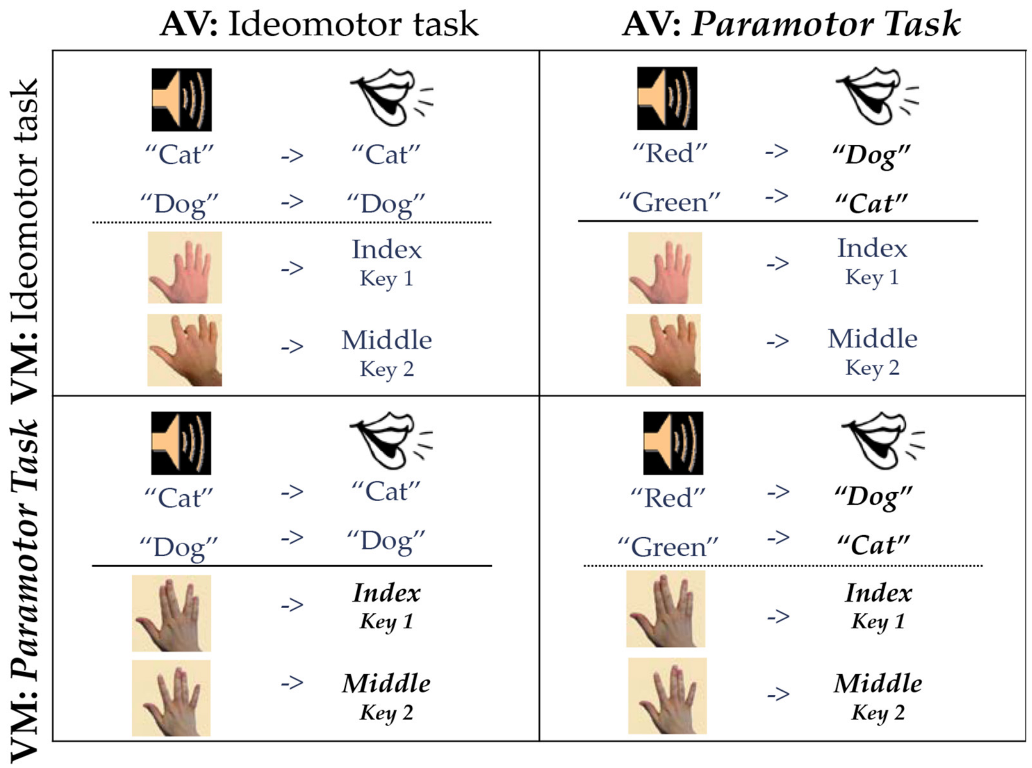

FIGURE 2 | Paramotor 2 × 2. Stimuli are on the left side of each quadrant, and responses are on the right side. Bold, italicized responses indicate PM tasks.

two stimuli simultaneously, we analyze the sum of the costs across the two tasks rather than examining costs for each task separately (see also, Halvorson et al., 2013; Halvorson and Hazeltine, 2015; Göthe et al., 2016). The block order, which was the AV task alone, the VM task alone, the OR block and lastly the AND block, was the same for all participants. Block order was kept consistent to reduce unnecessary uncertainty and to maximize the extent to which participants could prepare for the upcoming trials.

Planned Comparisons

There are two dependent measures of interest in this experiment: reaction time (RT) and accuracy. We plan three primary analyses based on RT data: single-task performance, mixing costs, and dual-task costs. To examine how the stimuli affect single-task performance, single-task RTs for each task will be submitted to a 2 × 2 ANOVA with two factors: task (IM or PM) and other task (same or different).

To evaluate mixing costs; we subtract mean RT on the single-task blocks from mean RT on the OR blocks. So that different task prioritization strategies do not contaminate this measure we sum the differences for the VM and AV tasks. In this way, we measure performance impairments associated with the strain of maintaining multiple task sets but only performing one response. The summed difference scores are submitted to a 2 × 2 ANOVA with two factors: VM compatibility (IM or PM) and AV compatibility (IM or PM). Both the spatial-verbal and set-level hypotheses predict significant mixing costs; these costs appear to be robust despite the configuration of S-R pairs within the tasks and the task sets in the pairing (see e.g., Halvorson et al., 2013; Halvorson and Hazeltine, 2015).

The focus of our study is dual-task costs; to obtain this measure we will calculate the difference between mean RT in the AND and OR blocks. Again, we sum the differences across the two tasks and submit them to an identical ANOVA to the one used to evaluate mixing costs. This ANOVA will indicate the presence of any additional cost incurred for simultaneously making two responses on each trial as opposed to one. According to the set-level hypothesis, there should be no significant main effects or interactions. According to the spatial-verbal hypothesis, dual-tasks costs should be larger when either task is a PM task.

Lastly, a single ANOVA will be conducted for the accuracy data with block type as the sole factor. This analysis indicates the extent to which participants successfully chose the correct response on each trial. We compare the results from the analysis to the corresponding one based on RT to assess speed-accuracy trade-offs.

Procedure

Each participant first completed the voice recognition training on the PC that was used to present the stimuli and collect responses. Following the vocal recognition training, participants were given verbal and written instructions for the AV and the VM tasks. They were told to respond as quickly and accurately as possible in both tasks; they were not instructed to prioritize either speed or accuracy. Participants were told that both tasks were equally important, and to make their responses as quickly and accurately as possible. In the AND blocks, they were instructed to do each task as fast as possible and not to prioritize either task.

Each trial proceeded as follows: first, the fixation cross appeared in the center of the screen. The fixation cross was white, 1.3° × 1.3° visual angle, and stayed on the screen for 500 ms. Then the auditory and visual stimuli were presented for 250 ms. After 2000 ms or a response, the next trial started. This was identical to the procedure in Halvorson and Hazeltine (2015).

PM PM Group

For the PM PM group (bottom right panel, **Figure 2**), the visual stimuli were images of hands in the position of either a "V" (two fingers were slanted to the left and two to the right) or a "W" (two fingers were straight up in the middle with the index finger separated to the left and the pinky finger separated to the right). Participants were instructed to press with the 1 or 2 key on the number pad with the right index or middle finger based on the instructions; mappings were counterbalanced across participants such that for half of the participants in this group the "V" image was mapped to the 1 key and for the other half the "V" image was mapped to the 2 key. For the AV task, the vocal responses "cat" and "dog" were randomly assigned (and counterbalanced) to the stimuli "red" and "green."

PM IM Group

For the PM IM group (top right panel, **Figure 2**) the PM AV task was paired with an IM VM task. In the IM VM task participants made a spatially compatible (L-R) response according to which finger was depressed in the image. If, for example, the index finger was depressed, participants were instructed to press the 1 key on the number pad with their right index finger. If the middle finger was depressed, participants pressed the 2 key on the number pad with their right middle finger.

IM PM Group

For the IM PM group (bottom left panel, **Figure 2**) the AV task used IM-compatible stimuli and responses (IM AV task). Participants were instructed to repeat the word they heard presented in their headphones so if the stimulus was "cat" participants would say the word "cat." This task was paired with the IM VM task using the "V" and "W" images counterbalanced to the index and middle fingers.

IM IM Group

For the IM IM group (top left panel, **Figure 2**) the IM AV and IM VM tasks were paired. Because this exact condition was used in the 2 × 2 reported in Halvorson and Hazeltine (2015), the data for this condition are taken from that paper. All methods, including the procedure and stimuli and responses, were identical to the methods reported here. The data for this group come from Group II in Halvorson and Hazeltine (2015); when first published, this condition was a straight replication of Experiment 3 in Halvorson et al. (2013).

RESULTS

Trials from the first of each block type, containing an incorrect response on either task, or resulting in RTs that exceeded 1500 ms or were shorter than 150 ms were eliminated from further analysis (9% of the remaining trials).

Single-Task RTs

Separate univariate 2 × 2 ANOVAs with compatibility (IM, PM) and task pairing (same, different) as between-subjects factors were conducted on single-task RTs for each task (see **Table 1**). For the AV task, there was a significant main effect of compatibility, $F(1,76) = 38.40$, $MSE = 6676.51$, $p < 0.001$, indicating faster overall RT when the S-R pairs were IM-compatible (325 ms) than PM-compatible (438 ms) and a significant main effect of pairing, $F(1,76) = 4.97$, $MSE = 6676.51$, $p < 0.05$, indicating faster mean RT when the pairing was different (e.g., IM paired with PM or vice versa; 361 ms) than when it was the same (402 ms). The interaction was also significant, $F(1,76) = 4.60$, $MSE = 6676.51$, $p < 0.05$. Follow-up t-tests revealed no significant difference between mean RT for the IM-compatible AV tasks when paired with the same (326 ms) or different (324 ms) VM task, $t < 1$. In other words, when it is IM-compatible, RT for the AV task is unaffected by the task with which it was paired. However, there was a significant difference between mean RT for the PM-compatible AV tasks when paired with the same (478 ms) or different (398 ms) VM task, $t(19) = 2.38$, $p < 0.05$.

TABLE 1 | Mean RT for the single-task, OR, and AND conditions of the AV and VM tasks for the four groups, standard errors in parentheses, accuracy at the bottom.

		AV: Ideomotor		**AV: *Paramotor***	
		AV	**VM**	**AV**	**VM**
		Group IM IM		**Group PM IM**	
VM: Ideomotor	Single	338	479	398	474
		(13)	(13)	(20)	(9)
		0.97	0.98	0.93	0.98
	OR	374	531	436	532
		(12)	(16)	(20)	(14)
		0.98	0.99	0.95	0.98
	AND	386	495	405	536
		(16)	(13)	(17)	(19)
		0.98	0.98	0.93	0.99
		Group IM PM		**Group PM PM**	
VM: *Paramotor*	Single	324	640	478	627
		(14)	(24)	(25)	(15)
		0.95	0.98	0.93	0.96
	OR	354	723	517	709
		(11)	(26)	(25)	(20)
		0.98	0.96	0.96	0.98
	AND	488	661	577	760
		(23)	(26)	(34)	(35)
		0.97	0.98	0.91	0.97

In other words, mean RT for the AV task was significantly slower when it was PM-compatible than when it was IM-compatible; mean RT for the AV task when it was PM-compatible was also affected by task pairing (unlike when it was IM-compatible). The AV PM tasks were 113 ms slower overall when paired with PM VM tasks than when paired with IM VM tasks. This suggests that task pairing had an effect even on single-task performance when no responses from the other task were required.

For the VM task, only the main effect of compatibility was significant, $F(1,76) = 95.25$, $MSE = 5226.71$, $p < 0.001$. Neither the main effect of pairing nor the interaction was significant, all Fs < 1. For the main effect of compatibility, overall RT was slower for PM-compatible S-R pairs (634 ms) than the IM-compatible S-R pairs (476 ms). Unlike the AV task, RT in the single-task conditions for the VM task was not significantly affected by task pairing. This suggests that performance on this task was not influenced differentially by the compatibility of the AV task during single-task blocks. For both the AV and VM tasks, RT was slower overall in the PM groups. This suggests the PM tasks, despite the similarities to the IM tasks, were more difficult to perform in isolation.

Mixing Costs

A 2 × 2 ANOVA with AV compatibility (IM, PM) and VM compatibility (IM, PM) was conducted for the sum of the mixing costs from the two tasks (**Figure 3**). The intercept was significant, $F(1,76) = 389.61$, $MSE = 2236.41$, $p < 0.001$, indicating significant mixing costs across groups (the mean mixing costs across all four conditions was 68 ms). Neither the main effect of the AV compatibility type, $F < 1$, VM compatibility type, $F(1,76) = 2.37$, $MSE = 5263.54$, $p = 0.14$, nor the interaction, $F < 1$, were significant. These findings indicate significant mixing costs across conditions that appear unaffected by the task pairing. In other words, the difficulty associated with maintaining multiple task sets influences RT even if a single response is being made and the magnitude of this cost appears relatively unaffected by the relationship between the tasks.

Dual-Task Costs

A 2 × 2 ANOVA with AV compatibility (IM, PM) and VM compatibility (IM, PM) as factors was conducted on the sum dual-task costs for the two tasks (**Figure 3**). The intercept was significant, $F(1,76) = 10.40$, $p < 0.05$, indicating the presence of significant dual-task costs. Neither the main effect of AV compatibility nor the interaction was significant, both $Fs < 1$, indicating no difference in the magnitude of the dual-task costs based on whether the AV task was IM- or PM-compatible. However, the main effect of VM compatibility was significant, $F(1,76) = 28.61$, $MSE = 9517.17$, $p < 0.001$, indicating greater overall dual-task costs when the VM task was PM-compatible (92 ms) than when the VM task was IM-compatible (−25 ms). The magnitude of the dual-task costs was determined by whether the VM task was PM compatible and did not appear to be affected by the compatibility of the AV task. In other words, essentially no dual-task costs were observed in the IM IM or PM IM groups. Significant dual-task costs were observed in the IM PM and PM PM groups[4].

Accuracy

Accuracy data were collapsed across tasks for each task and submitted to a one-way ANOVA with block type as a within-subjects factor. In the PM PM group there was a main effect of block type, $F(2,38) = 9.82$, $MSE = 0.001$, $p < 0.001$. There was no difference between the single task (94%) and AND (94%) blocks, $t < 1$, but there was a significant difference between the OR (97%) and the single, $t(39) = 3.33$, $p < 0.01$, and the OR and the dual-task blocks, $t(39) = 3.18$, $p < 0.01$, indicating higher accuracy in the OR than the single- or dual-task blocks. It does not appear that the pattern of mixing- and dual-task costs are contaminated by speed-accuracy tradeoffs, however, as the main effect of block type was not significant for the PM IM, $F(2,38) = 2.11$, $p = 0.14$, IM PM, $F(2,38) = 2.80$, $p = 0.07$, or IM IM, $F(2,38) = 1.23$, $p = 0.30$, groups. Because the main effect was not observed consistently with task pairings that give rise to dual-task interference nor those that do not, it is not likely that the observed main effect in the PM PM group can account for the main differences in RT reported previously.

DISCUSSION

The task pairings reported here were designed to investigate whether previously reported findings of minimal dual-task costs observed with IM-compatible stimuli were the result of compatible relationships between the stimulus and response *sets* for each task. The set-level hypothesis holds that the images of hands and spoken words evoke their manual keypresses and vocal utterance, respectively, so that the tasks using these S-R pairings can be performed simultaneously without interference. This hypothesis explains previous findings of minimal dual-task costs with tasks that used these task pairings even when the mappings between the individual stimuli and responses in the sets that were not IM-compatible. However, the findings from the current experiment did not support such an account; costs

[4]Although this measure of dual-task costs includes the additional strain on dual-task trials of keeping two tasks active, trials in the OR blocks contain an additional task switch component that may not be present on AND trials. To isolate the influence of a potential switch cost in the OR blocks on the overall magnitude of the dual-task costs, we can make a stringent comparison between trials from the AND and OR blocks in which the switch costs were relatively equal. When we look at the difference between only trials from the AND blocks in which the response on each task alternated with trials from the OR blocks in which the task repeated but the alternate response was required we see a very similar pattern of dual-task costs. A 2 × 2 ANOVA with AV compatibility (IM, PM) and VM compatibility (IM, PM) was conducted on the stringent dual-task costs. The intercept was significant, indicating the presence of significant dual-task costs, $F(1,76) = 17.94$, MSE = 10165.18, $p < 0.001$. Neither the main effect of AV nor the interaction was significant, $F < 1$ and $F(1,76) = 1.84$, $p = 0.19$, respectively, indicating no difference in the magnitude of the costs based on the compatibility of the AV task. The main effect of VM compatibility was significant, $F(1,76) = 27.30$, MSE = 10165.18, $p < 0.001$. There were greater dual-task costs when the VM task was PM-compatible (115 ms) than when it was IM-compatible (−19 ms). In other words, even with a very stringent measure, there were robust dual-task costs in the IM PM (91 ms) and PM PM (139 ms) groups and no costs in the IM IM (−4 ms) and PM IM (−35 ms) groups.

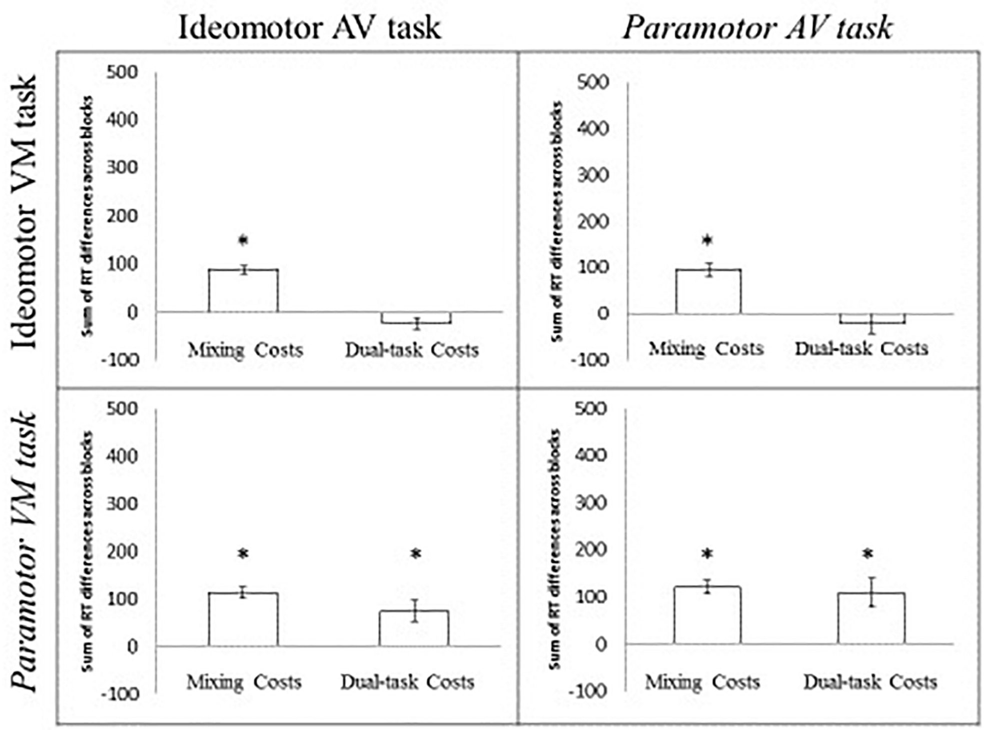

FIGURE 3 | Sum of the mixing and dual-task costs for the PM 2 × 2. Error bars indicate the standard error of the mean. The asterisk indicates a significant cost (greater than 0) at the 0.05 level.

were observed when the PM VM task (which also used images of hands) was paired with both AV tasks.

Strikingly, subtle differences in the VM stimuli used in these groups produced distinct patterns of results – both in the single-task blocks and when paired with the AV tasks. This suggests that changing the shape made of the hand made the task more difficult in some way. One possibility is that the PM visual stimuli were more complex than the IM visual stimuli. However, previous dual-task experiments using variations of images of hands as visual stimuli have shown that overall RT can vary independently from the magnitude of the dual-task interference (see e.g., Halvorson et al., 2013; Halvorson and Hazeltine, 2015). Thus, it appears that the spatial mapping is the key factor giving the IM tasks the advantage.

With regard to the dual-task costs, we contend that the changes to the visual stimuli made it so that the PM VM task was not restricted to the spatial domain. Note that this task resulted in dual-task interference with both AV tasks while the IM VM task did not. It is possible that the use of the letter shapes in the description of the stimuli to the participants (a "V" or "W") may have caused participants to adopt a verbal label for the stimuli in the VM task requiring the activation of verbal information during response selection, causing crosstalk between tasks. If so, it is striking that this difference in the IM and PM visual stimuli produces large differences in dual-task costs. Both sets are images of hands in naturalistic postures seen from the approximate perspective of the subject. If seeing an image of a hand directly activated the manual responses and eliminated dual-task interference with an AV task, then the precise shape of the hand or whether a semantic code was used to identify the stimulus should not matter. Moreover, although the stimuli were described with letters, participants were not required to name each stimulus or give a verbal response to the images of hands; they only had to match the visual information on the screen with the correct keypress. Thus, as in the IM VM task, verbal codes were not required for completing the PM VM task. It is notable that participants were unable to avoid using these codes to minimize interference if the codes are indeed the source of the costs.

Two limitations should be kept in mind, first, we were forced to use a between-subjects design to avoid carry-over effects and we were unable to test our groups for equivalency with regard to performance on each task. Second, we did not independently assess the discriminability of the IM and VM stimuli, although, based on inspection, it appears unlikely that the PM stimuli are less discriminable.

This pattern of results is consistent with the spatial-verbal hypothesis. As in Wickens' (1984) resource model, this hypothesis suggests that the extent to which two tasks interfere with each other depends critically on whether the two tasks can be processed in distinct domains; specifically, whether one task consists entirely of visual-spatial-manual information and the other consists of auditory-verbal-vocal codes.

However, the spatial-verbal hypothesis also predicted dual-task costs for task pairings involving the PM AV task, and this pattern of results was not observed. Results from a recent implicit learning study offer insight into why dual-task costs may not have been incurred when the PM AV task was paired with the IM VM task. Eberhardt et al. (2017) showed that participants could not learn a stimulus location sequence and a response location sequence simultaneously when both sequences used spatial codes. They could, however, learn distinct stimulus and response sequences simultaneously when one of them was coded as a color-sequence; this allowed the learning of the location sequence to take place without interference. Similarly, the Queueing Network-Model Human Processor, which models human behavior during concurrent driving tasks and multitasking performance more broadly, assumes that tasks can share resources in the central processing domain and that interference occurs most often when tasks compete for peripheral (e.g., visual) resources (Liu et al., 2006). Taken together, these findings begin to address the nature of the codes described in Wickens' (1984) theory and what causes crosstalk. Future studies should continue to investigate the boundary conditions of highly efficient dual-task performance using AV tasks with spatial VM tasks to determine whether there are conditions under which the semantic content of the words or other auditory sounds used as stimuli result in significant interference with a spatial VM task.

More broadly, these findings contribute to a growing body of work suggesting a critical role for input- and output-modality pairings in predicting the magnitude of the interference between two tasks (e.g., Navon and Miller, 1987; Hazeltine et al., 2006; Janczyk et al., 2014). Dual-task research has benefited from the framework provided by Hazeltine et al. (2006), whose seminal finding challenged the assumption of a content-independent central processor and made the case for a theory of dual-task performance that depends critically on the modalities of the S-R pairs. Their practice studies were among the first findings that emphasized the importance of the modality pairings – both within and between tasks. Recently, Maquestiaux et al. (2017) investigated the role of sensory-motor modality compatibility (a term first introduced by Stephan and Koch (2011) in a converging line of work investigating the role of stimulus and response modalities on task switching costs) in bypassing the bottleneck. The findings from this study showed that after extensive practice, only task pairings that were sensory-motor modality compatible (i.e., AV and VM) resulted in highly efficient dual-task performance indicative of bottleneck bypassing. Task pairings that were sensory-motor modality incompatible (auditory-manual and visual-vocal) did not show evidence of bottleneck bypassing.

There is also broad speculation that the specific influence of modality pairings on dual-task performance stems from the organization of the working memory subsystems (Baddeley and Hitch, 1974) that are presumably engaged during the task (Halvorson et al., 2013; Halvorson and Hazeltine, 2015; Maquestiaux et al., 2017). When the stimuli, central binding processes, and responses for one task can be entirely contained in one working memory subsystem (e.g., the AV task in the articulatory loop) and the other task is entirely contained in a distinct subsystem (e.g., the VM task in the visuospatial sketchpad), then the two tasks will not interfere.

In sum, although there have been several recent findings of highly efficient dual-task performance when one task uses images of hands as stimuli mapped to manual responses (e.g., Halvorson et al., 2013; Halvorson and Hazeltine, 2015), it does not appear to be the case that this is the result of an direct activation link between seeing images of hands and pressing buttons or hearing words and saying a vocal response. It is more likely that the lack of interference was the result of the extent to which the two tasks can be kept separate by virtue of the lack of crosstalk (or some other form of interference) between the component parts for each task. The interference observed here can be explained by such an account. Future studies should examine the precise nature of the information that leads to crosstalk.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Code of Federal Regulations, Department of Health and Human Services, Protection of Human Subjects. The protocol was approved by the University of Iowa Institutional Review Board. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

KH and EH contributed to the conception and design of the study. KH performed the statistical analysis and wrote the first draft of the manuscript. EH contributed to the manuscript revisions. Both authors read and approved the submitted version.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 06 November 2018
doi: 10.3389/fpsyg.2018.01942

Dual-Tasking in the Near-Hand Space: Effects of Stimulus-Hand Proximity on Between-Task Shifts in the Psychological Refractory Period Paradigm

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Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to
Movement Science and Sport
Psychology,
a section of the journal
Frontiers in Psychology

Received: 04 March 2018
Accepted: 20 September 2018
Published: 06 November 2018

Citation:
Hosang TJ, Fischer R, Pomp J
and Liepelt R (2018) Dual-Tasking
in the Near-Hand Space: Effects
of Stimulus-Hand Proximity on
Between-Task Shifts
in the Psychological Refractory Period
Paradigm. Front. Psychol. 9:1942.
doi: 10.3389/fpsyg.2018.01942

Two decades of research indicate that visual processing is typically enhanced for items that are in the space near the hands (near-hand space). Enhanced attention and cognitive control have been thought to be responsible for the observed effects, amongst others. As accumulating experimental evidence and recent theories of dual-tasking suggest an involvement of cognitive control and attentional processes during dual tasking, dual-task performance may be modulated in the near-hand space. Therefore, we performed a series of three experiments that aimed to test if the near-hand space affects the shift between task-component processing in two visual-manual tasks. We applied a Psychological Refractory Period Paradigm (PRP) with varying stimulus-onset asynchrony (SOA) and manipulated stimulus-hand proximity by placing hands either on the side of a computer screen (near-hand condition) or on the lap (far-hand condition). In Experiment 1, Task 1 was a number categorization task (odd vs. even) and Task 2 was a letter categorization task (vowel vs. consonant). Stimulus presentation was spatially segregated with Stimulus 1 presented on the right side of the screen, appearing first and then Stimulus 2, presented on the left side of the screen, appearing second. In Experiment 2, we replaced Task 2 with a color categorization task (orange vs. blue). In Experiment 3, Stimulus 1 and Stimulus 2 were centrally presented as a single bivalent stimulus. The classic PRP effect was shown in all three experiments, with Task 2 performance declining at short SOA while Task 1 performance being relatively unaffected by task-overlap. In none of the three experiments did stimulus-hand proximity affect the size of the PRP effect. Our results indicate that the switching operation between two tasks in the PRP paradigm is neither optimized nor disturbed by being processed in near-hand space.

Keywords: dual task, cognitive control, psychological refractory period (PRP), multitasking, near-hand space, embodied cognition, attention, peripersonal space

INTRODUCTION

The human visual system evolved to not only perceive the world, but also to enable physical interaction with the environment (Goodale, 2011). More than 20 years of research support this reasoning, showing altered visual processes close to one of the main human effectors, the hands. Typically, performance is assessed using different stimulus-hand proximities, comparing a condition in which stimuli are presented close to the hands (near-hand condition) and a condition in which stimuli are presented further away from the hands (far-hand condition). Earliest accounts of altered visual processing in near-hand space was provided by Hari and Jousmaki (1996), showing faster reaction times (RTs) when visual stimuli were presented near the hands. Their results indicated prioritized visual processing of stimuli in the near-hand space (near-hand effect). A number of neuropsychological studies subsequently provided supporting findings for this effect, reporting improved visual processing in the near-hand space in patients with extinction (di Pellegrino et al., 1997; di Pellegrino and Frassinetti, 2000) and hemianopsia (Schendel and Robertson, 2004).

Since these findings were obtained, considerable effort has been put into exploring behavioral performance in healthy individuals during visual cognition tasks in the near-hand space (for reviews see Tseng et al., 2012; Brockmole et al., 2013; Abrams et al., 2015; Goodhew et al., 2015; Thomas and Sunny, 2017). Study findings have shown that, for example, task processing in near-hand space includes increased visual working memory performance (Tseng and Bridgeman, 2011), emphasized magnocellular information processing (Gozli et al., 2012; Goodhew et al., 2014), enhanced cognitive control (Wang et al., 2014; Weidler and Abrams, 2014; Liepelt and Fischer, 2016), and enhanced attention (Reed et al., 2006; Abrams et al., 2008). Moreover, visual processing in the near-hand space can be biased, not only by the mere presence of the hands, but also by the specific hand-posture (Thomas, 2015), plasticity (Makin et al., 2010; Reed et al., 2017; Thomas, 2017), and task-demands (Goodhew and Clarke, 2016; Liepelt and Fischer, 2016). In summary, the available literature indicates that stimuli and tasks are processed differently in the near-hand space. These effects can be traced back to diverse alterations that range from changes in early perceptual processing to changes in cognitive control (Tseng et al., 2012; Brockmole et al., 2013; Abrams et al., 2015; Goodhew et al., 2015; Thomas and Sunny, 2017).

It is important to note that almost all of the evidence for the near-hand effect comes from single-task experiments, in which only one stimulus is attended to and only one task is processed. Cognitive control and attentional processes, among others, were held responsible for the observed effects. There is accumulating experimental evidence (Liepelt et al., 2011; Fischer and Hommel, 2012) and theoretical rationale (Meyer and Kieras, 1997; Logan and Gordon, 2001) that suggests the involvement of cognitive control processes during the scheduling and coordination of two simultaneous tasks (dual tasking). If near hand space alters cognitive control and attention (Abrams et al., 2008; Wang et al., 2014; Weidler and Abrams, 2014; Liepelt and Fischer, 2016) and between-task shifts during dual tasking involve cognitive control and attention (Meyer and Kieras, 1997; Logan and Gordon, 2001; Luria and Meiran, 2003; Koch et al., 2018), one should predict a modulation of dual-tasking performance in the near-hand space as compared to far-hand space. Also, societal and technological advances have increased the demands on multimedia multitasking and the complexity of human-technological interactions. The common use of hand-held devices, for example, shifts the visual-manual interaction into a single visuo-spatial region. To date, it remains unclear how the near-hand space affects one's processing of multiple stimuli in the visual display that are assigned to different tasks. The aim of the present study is to investigate the impact of stimulus-hand proximity in a dual-task situation in which the stimulus (Stimulus 1) of Task 1 is presented on the right and requires responses with the right hand and the stimulus (Stimulus 2) of Task 2 is presented on the left and requires responses with the left hand. We use the psychological refractory period (PRP) paradigm to test the efficiency of the shifting process between Task 1 and Task 2 processing under dual-task conditions. The PRP paradigm allows for an exact assessment of Task 1–Task 2 shifts due to the precise experimental manipulation of the temporal overlap of two tasks. The better Task 2 performance at short SOAs (i.e., indexed by the size of the PRP effect), the more efficient the engagement of Task 2 processing. The PRP paradigm thus represents a perfectly suitable approach to precisely measure the shifting operation in dual-task contexts.

It has previously been indicated that, in single-task studies, the benefit of increased in-depth visual processing of an attended stimulus comes at the cost of delayed disengagement from this stimulus (e.g., Abrams et al., 2008). For example, the effects of inhibition of return (i.e., costs of re-allocating attention to previously engaged locations) have been shown to be decreased in near-hand space, a finding that was interpreted as slower disengagement from the originally attended location of stimulus processing. This interpretation has been further substantiated by the findings of Abrams et al. (2008) showing an increased attentional blink effect in near-hand space (Abrams et al., 2008). The attentional blink characterizes the inability to detect a second target presented in rapid succession to a first one (Raymond et al., 1992; Shapiro et al., 1997). In particular, participants were required to report the parity of a digit (Stimulus 1) and then the identity of a letter (Stimulus 2) that was presented at various intervals following Stimulus 1. While the typical pattern of the attentional blink was found in the far-hand condition, this inability to detect Stimulus 2 within short succession of Stimulus 1 was much more pronounced when participants' hands were close to the stimuli. Taken together, these findings suggest that increased in-depth visual processing of an attended stimulus in near-hand space might result in costs when switching the processing of one stimulus to another stimulus.

The findings from a sequential dual-task study (i.e., task switching) by Weidler and Abrams (2014) are, however, quite the opposite. The authors, suspecting an increased engagement of cognitive control processes in near-hand compared to far-hand conditions, tested a task-switching paradigm. Participants were presented with bivalent stimuli (i.e., colored geometrical figures) while a cue indicated which task had to be performed (i.e., color or shape discrimination). The important factor was the repetition or alternation of task type, as there are typically larger performance costs when tasks alternate rather than repeat. Such task switching costs are thought to be a marker for flexible updating and reconfiguration of task sets (Monsell, 2003; Kiesel et al., 2010; Vandierendonck et al., 2010; Koch et al., 2018). Importantly, Weidler and Abrams (2014) found reduced switching costs in near-hand compared to far-hand conditions. These findings were interpreted as evidence for an increased level of cognitive control involvement during near-hand conditions. Although this is in line with other reports of increased cognitive control in near-hand space (e.g., Davoli et al., 2010; Liepelt and Fischer, 2016), the mechanisms by which stimulus-hand proximity might reduce switching costs have not yet been identified. Current explanations range from an increased maintenance of task instructions to the activation of the correct S-R translation rule (Weidler and Abrams, 2014) due to enhanced cue processing. In any case, these findings show that shifts between two different task sets seem to be less costly when stimuli are presented in near-hand space.

Overall, the existing literature offers only inconclusive assumptions with regard to the question how the processing of multiple stimuli might be affected when stimuli are presented in near-hand space and how this differs from far-hand conditions. In dual tasks, processing of the stimulus in Task 1 is accompanied by additionally processing the stimulus in Task 2. While early perceptual processes might occur at the same time, at some point processing must shift from Task 1 to Task 2 (see below for more details). If each stimulus is spatially presented to a separate response hand (e.g., Stimulus 1 near the right hand and Stimulus 2 near the left hand), it remains unclear how hand proximity affects this processing shift between tasks.

Evidence from visual attention studies (e.g., Abrams et al., 2008) suggests that near-hand beneficial processing of Stimulus 1 results in delayed disengagement. Hand-nearness facilitates attentional processing of the respective stimulus (e.g., Stimulus 1). This however, might induce cost when shifting processing from Stimulus 1 to Stimulus 2 is required in a dual task. Evidence from task switching studies, however, indicates the opposite. Reduced task switching costs in near-hand space suggest beneficial switching between different task sets (Weidler and Abrams, 2014). Here, the attentional benefit of processing stimuli in near hand space might extend to both, Stimulus 1 and Stimulus 2, easing the shifts between the two stimuli. Thus, by investigating dual-task performance in different stimulus-hand proximity conditions, we learn whether and to which extent the attentional consequences of hand nearness affect the processing shift between two tasks.

In the present study, we apply a PRP dual-task paradigm that allows the investigation of simultaneous task component processing. In particular, two RT tasks are presented with varying temporal intervals [stimulus onset asynchrony (SOA)]. Participants are instructed to respond with their right hand to an initial visual stimulus (Stimulus 1) presented on the right and then to respond with their left hand to a second stimulus (Stimulus 2) presented on the left. Whereas Task 1 processing is mostly unaffected by SOA, RTs for Task 2 typically increase with decreasing SOA between both tasks. Impaired Task 2 performance at short compared to long SOA is known as the PRP effect (Welford, 1952; Pashler, 1994). The PRP effect is commonly attributed to a capacity limitation (e.g., processing bottleneck) and it is assumed that a central cognitive stage in Task 1 has to be completed before processing of that stage of Task 2 can proceed. Although the existence of a processing bottleneck is widely accepted, there is still a debate over its exact nature (i.e., whether it is structural, strategic, or functional) (Pashler, 1994; Meyer and Kieras, 1997; Logan and Gordon, 2001; Tombu and Jolicœur, 2003; Fischer and Plessow, 2015; Broeker et al., 2017). As with task switching, the involvement of cognitive control processes in scheduling and coordinating the simultaneous performance of two tasks has been advocated by many authors (Meyer and Kieras, 1997; Logan and Gordon, 2001; Luria and Meiran, 2003; Liepelt et al., 2011; Koch et al., 2018). Even though task priority is typically given to the first task (Task 1), at a given point in time task processing has to shift to Task 2, which can occur passively (Pashler, 1994) or can be realized by cognitive control parameters optimizing task (dis)engagement (Meyer and Kieras, 1997; Logan and Gordon, 2001). Currently, it is not clear whether near-hand space affects this Task 1–Task 2 processing shift in dual tasking. This is surprising given that the processing of multiple stimuli and tasks is an increasingly prevalent aspect of daily human-technology interaction. Investigating the effects of stimulus-hand proximity on PRP performance holds the potential to get further insights into how stimulus-hand proximity and corresponding changes in cognitive control affects switching operations during the PRP paradigm (Meyer and Kieras, 1997; Logan and Gordon, 2001).

If the near-hand space results in delayed disengagement from processing the prioritized Stimulus 1 (Abrams et al., 2008), shifts from Task 1 to Task 2 processing should be prolonged, resulting in an increased PRP effect for near-hand compared to far-hand conditions. Alternatively, if the near-hand space facilitates switching between two tasks sets (Weidler and Abrams, 2014), shifts from Task 1 to Task 2 processing should benefit from near-hand conditions. This should result in a reduced PRP effect when hands are located near the stimuli.

EXPERIMENT 1

In Experiment 1, we used a dual-task paradigm adapted from the PRP literature (Fischer et al., 2007). The paradigm was chosen to specifically test the effect of the near-hand space on Task 1–Task 2 switching by means of the PRP effect. Task 1 was a number categorization task wherein numbers had to be categorized into either odd or even. For Task 2, participants had to perform a letter categorization task wherein letters had to be categorized as either a vowel or a consonant. Stimulus 1 was first presented on the right side of the screen and required responses with the right hand. Stimulus 2 appeared on the left side and required responses with the left hand. For the near-hand condition response buttons were placed on the monitor. For the far-hand condition response buttons were placed on the lap.

Methods

Participants

Thirty-six participants from the Dresden University of Technology (28 female; M_{age} = 25.1 years, SD = 5.6) were tested. Participants received either course credits or monetary reward for their participation. All participants had normal or corrected-to-normal vision. All but three of the participants claimed to be right-handed. Written informed consent was provided by all participants prior to their participation in the experiment. All experiments were conducted in accordance with the ethical standards of both the 1964 Declaration of Helsinki and the German Psychological Association.

Design

A 2 (stimulus-hand proximity: near vs. far) × 4 (SOA: 40, 130, 300, and 900 ms) within-subjects repeated measures design was applied.

Stimuli and Apparatus

The digits 2, 3, 7, and 8 served as Stimulus 1 for Task 1. Stimulus 1 were presented on the right side (+5.3 cm from screen center) of a 17-inch TFT-monitor (1280 × 1024 pixel resolution). For Task 2 the letters A, K, M, and U were used as Stimulus 2. Stimulus 2 were presented on the left side of the computer screen (−5.3 cm from screen center), see **Figure 1A**. All stimuli were presented on a black background in Arial font (white). The viewing distance was set to approximately 45 cm, while the total presentation field extended to a visual angle of 14.2° horizontally and 1.3° vertically. The visual angle of all the the stimuli extended to 0.76° horizontally and 1.27° vertically.

Two manual response buttons were assigned to each hand (see **Figure 2**). Elbow angle, as well as the distance and spatial orientation of the response buttons was held constant between the near-hand condition and the far-hand condition. Participants responded with the index (odd numbers) and middle finger (even numbers) of their right hand to Stimulus 1 and with the index (vowel letters) and middle finger (consonant letters) of their left hand to Stimulus 2. The index fingers activated the upper buttons, while the middle fingers activated the lower buttons. For the near-hand condition the buttons were vertically arranged on the right and left sides of the computer monitor. Button placement matched the height of stimulus presentation. For the far-hand condition, the response buttons were analogously positioned on the left and right sides of a wooden board that rested on the participants' knees. The distance between left and right response buttons of the far-hand condition (board) was matched to that of the near-hand condition (monitor).

Presentation of the stimuli and data recording was carried out using the Software Presentation (Version 16.5; Neurobehavioral Systems, Inc., Albany, CA, United States) on a Windows PC (Win7, Intel Core i5-6500 [2.6 GHz, 6MB]).

Procedure

A fixation started each trial (500 ms; central white cross). Stimulus 1 presentation (right side of the screen) was followed by Stimulus 2 presentation (left side of the screen) with varying

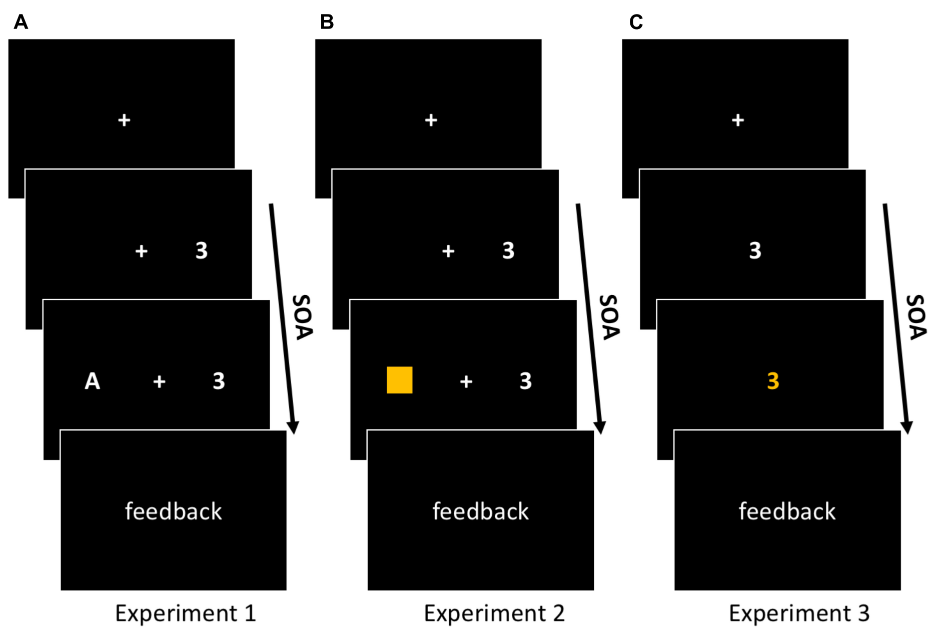

FIGURE 1 | Schematic illustration of the three PRP experiments. In all three experiments Task 1 and Task 2 were presented with varying stimulus-onset asynchrony (SOA). **(A)** In Experiment 1, participants had to categorize digits (2, 3, 7, 8) into odd or even (Task 1) and letters (A, K, M, U) as either vowels or consonants (Task 2). **(B)** In Experiment 2, Task 1 was the same as in Experiment 1. Task 2 was a color-categorization task, where the color of a rectangle had to be categorized into either orange or blue. **(C)** In Experiment 3, Task 1 and Task 2 were the same as in Experiment 2, but they were presented as a single bivalent stimulus. The number stimulus relevant for Task 1 changed its color initiating the color categorization for Task 2. In all of the three experiments trials began with a fixation and ended with the provision of feedback in the form of the German words *richtig* (correct), *falsch* (incorrect), or *zu langsam* (too slow).

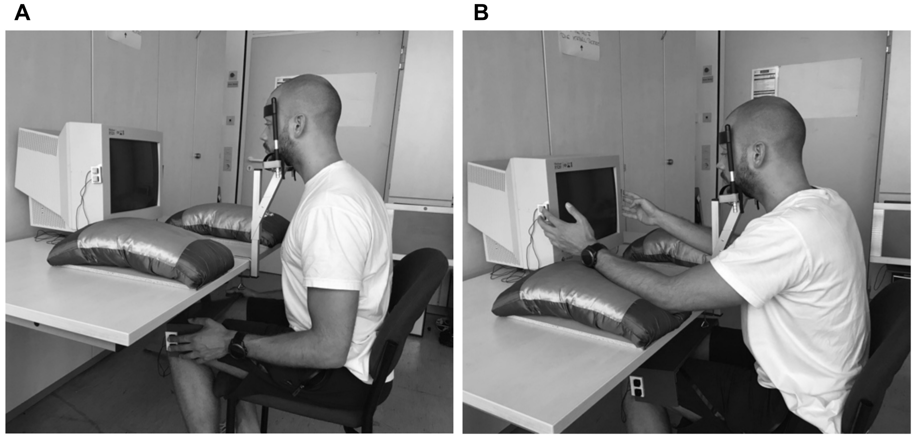

FIGURE 2 | Experimental setup during the far-hand condition **(A)** and the near-hand condition **(B).**

temporal interval (SOA, 40, 130, 300, and 900 ms). Stimulus 1 and Stimulus 2 remained on the screen for 1000 ms. Button press in response to Stimulus 1, and Stimulus 2 initiated the ending of the trial. No response or a single button press response resulted in the abortion of the trial after a maximum of 2500 ms after Stimulus 2 offset. Feedback was given in the form of the German words *richtig* (correct), *falsch* (incorrect), or *zu langsam* (too slow) for the duration of 500 ms. Subsequent trials started after a random and variable (100–1000 ms in steps of 100 ms) response-fixation interval.

Subjects were instructed to perform Task 1 and Task 2 as fast and as accurate as possible while processing priority was instructed on Task 1. They were further instructed to not delay Task 1 response to avoid response grouping. Task 1 was a number categorization task (odd vs. even) and Task 2 was a letter categorization task (vowel vs. consonant).

The experiment had a near and far-hand condition, each comprising 3 blocks. One block contained 64 trials (16 trials per SOA). Thus, 192 trials were performed per stimulus-hand proximity condition, which equals 384 trials in total. Both conditions started with a familiarization phase (16 practice trials). During this phase the instructor was present, answered questions, and ensured that the hand position was correct. A brief break was given after each block.

Results

A repeated measures ANOVA was conducted on RTs and percent error (PE) in both tasks and included the within-subject factors stimulus-hand proximity and SOA. For RT analyses (Task 1 RTs and Task 2 RTs) error trials in either task (9.2%), and trials that were below 150 ms or above 3000 ms (<0.1%) were excluded prior to analysis. Double-errors (Task 1 and Task 2 errors) were excluded prior to Task 2 error analyses (<1.1%). Greenhouse–Geisser correction was applied in case of violation of sphericity. RTs and PEs are presented in **Table 1**. RTs are further depicted in **Figure 3**.

Task 1 RTs

There was no main effect of stimulus-hand proximity, $F < 1$. Also, we found no main effect of SOA, $F(3,105) = 1.54$, $p = 0.188$, $\eta_p^2 = 0.05$. Furthermore, we found no significant interaction of the factors stimulus-hand proximity and SOA, $F < 1$.

Task 1 PEs

There were no significant main effects of the factors stimulus-hand proximity, $F < 1$ and SOA, $F(3,105) = 1.76$, $p = 0.160$, $\eta_p^2 = 0.05$. There was further no significant interaction of stimulus-hand proximity and SOA, $F < 1$.

Task 2 RTs

We found no main effect of stimulus-hand proximity, $F < 1$. However, statistical analysis revealed a significant effect for

TABLE 1 | Mean reaction times (RT in ms) and mean errors (PE in %) for Task 1 and Task 2 in Experiment 1.

		SOA	Near	Far
Task 1	RT	40	840 (30)	838 (33)
		90	828 (29)	836 (36)
		300	843 (36)	826 (37)
		900	876 (50)	875 (56)
	PE	40	4.8 (0.9)	4.5 (0.9)
		90	4.1 (0.7)	4.5 (0.9)
		300	3.6 (0.7)	3.5 (0.7)
		900	4.2 (0.7)	3.7 (0.8)
Task 2	RT	40	1152 (36)	1131 (32)
		90	1057 (34)	1055 (37)
		300	932 (37)	905 (34)
		900	680 (28)	665 (26)
	PE	40	5.3 (0.8)	6.1 (1.0)
		90	4.5 (0.8)	6.6 (1.1)
		300	5.5 (1.0)	5.6 (1.1)
		900	3.7 (0.7)	4.0 (0.9)

Standard errors of the mean in parentheses. SOA, stimulus onset asynchrony.

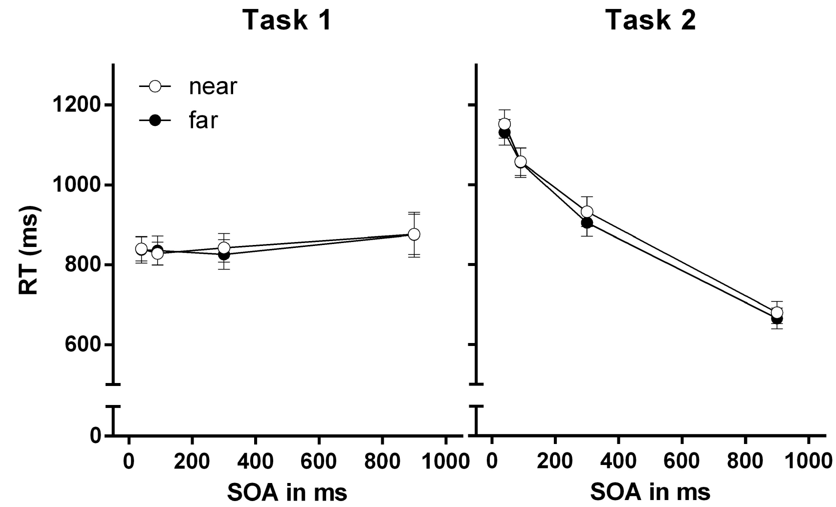

FIGURE 3 | Reaction times (RTs) for Task 1 and Task 2 for the near-hand and far-hand condition in Experiment 1. Error bars represent standard errors of the mean.

the factor SOA, $F(3,105) = 524.19$, $p < 0.001$, $\eta_p^2 = 0.94$ revealing decreasing RTs with SOA increase. We observed no significant interaction of stimulus-hand proximity and SOA, $F < 1$.

Task 2 PEs

We observed no main effect of the factor stimulus-hand proximity, $F < 1$. A significant main effect of the factor SOA was found, $F(3,105) = 5.14$, $p = 0.002$, $\eta_p^2 = 0.13$, revealing decreased PEs with increasing SOA. No interaction of the factors stimulus-hand proximity and SOA was found, $F(3,105) = 1.61$, $p = 0.192$, $\eta_p^2 = 0.04$.

Discussion

The results of Experiment 1 reveal two main findings. First, the characteristic dual task result pattern was identified, revealing the standard PRP effect: Task 1 RT and Task 1 PEs performance was not affected by temporal overlap between tasks, whereas Task 2 RTs and Task 2 PEs declined with increasing SOA (Pashler, 1994). Second, stimulus-hand proximity did not affect dual-task performance. No modulation of the PRP effect by stimulus-hand proximity was observed on the level of RTs and PE. Accordingly, the efficiency of the Task 1–Task 2 shifting process was not modulated in the near-hand space, at least not for a typical variant of the PRP dual-task paradigm. This indicates that the shifting operation in the PRP paradigm is quite robust against near-hand space-induced modulations of attention and cognitive control.

EXPERIMENT 2

In Experiment 2 we performed a second dual-task experiment to investigate the effect of stimulus-hand proximity on Task 1–Task 2 switching using a PRP dual-tasking paradigm where Task 1–Task 2 switching had to occur between a color and a form-categorization task. A previous task-switching study found reduced switching costs when participants had to switch from a form-categorization task to a color-categorization task (Weidler and Abrams, 2014). In contrast, Experiment 1 involved a PRP dual-task paradigm in which shifts from Task 1 to Task 2 processing had to occur between two number-categorization tasks. It was our assumption, that distinct switching operations may be differentially susceptible to near-hand space. This assumption was further substantiated by a study in which subjects had to perform task-switches during a local/global task (i.e., judging either local or global aspects of objects) (Davoli et al., 2012). Contrary to the Weidler and Abrams (2014) experiment, the results provided by Davoli et al. (2012) revealed slower switching during near-hand, compared to far-hand, conditions. Thus, for Experiment 2, we adapted the switching operation of Experiment 1 by implementing a color categorization task for Task 2, while Task 1 remained unchanged (see **Figure 1B**). During Task 2, participants had to decide if the color of a rectangle was either orange or blue. The rest of the set-up and predictions were identical to Experiment 1.

Methods

Participants

A sample of 36 participants from the University of Münster, Germany (24 female; $M_{age} = 23.7$ years, $SD = 6.5$) took part in the experiment. Participants received either course credits or monetary reward. All participants had normal or corrected-to-normal vision. All participants were right-handed. Written informed consent was provided by all participants prior to their inclusion in the experiment. One participant was excluded from further data analysis due to high error rates ($M_{total} = 31.64\%$) surpassing 3 *SD*s of the overall total error rates ($M_{total} = 9.26\%$). The remaining 35 subjects were included in for further data analysis.

Design

A 2 (Stimulus-hand proximity: near vs. far) × 4 (SOA: 40, 130, 300, and 900 ms) within-subjects repeated measures design was applied.

Stimuli, Apparatus, and Procedure

Task 1 in Experiment 2 was identical to Task 1 in Experiment 1. For Task 2, a blue and an orange colored rectangle served as stimuli (Stimulus 2). The position of stimulus presentation was the same as in Experiment 1. Subjects responded with the index (odd numbers) and middle finger (even numbers) of their right hand to Stimulus 1. The index (orange rectangle) and middle finger (blue rectangle) of their left hand was used to respond to Stimulus 2. The rest of the set-up was identical to Experiment 1, except that a chin rest was used to maintain a stable head position. The experiment had a near and far-hand condition, each comprising two blocks. One block contained 64 trials (16 trials per SOA). Thus, 128 trials were performed per stimulus-hand condition, which equals 256 trials in total. The rest of the procedure was identical to Experiment 1.

Results

A repeated measures ANOVA was conducted on RTs and PEs in both tasks and included the factors stimulus-hand proximity, as well as SOA as within-subject factors. For RT analyses (Task 1 RTs and Task 2 RTs), error trials in either task (9.26%), and trials with RTs below 150 ms or above 3000 ms (<0.1%) were excluded prior to analysis. Double-errors (Task 1 and Task 2 errors) were excluded for Task 2 error analyses (<1.8%). Greenhouse–Geisser correction was applied in case of violation of sphericity. RTs and PEs are presented in **Table 2**. RTs are further depicted in **Figure 4**.

TABLE 2 | Mean reaction times (RT in ms) and mean errors (PE in %) for Task 1 and Task 2 in Experiment 2.

		SOA	Near	Far
Task 1	RT	40	779 (28)	817 (33)
		90	774 (31)	816 (34)
		300	780 (31)	801 (36)
		900	779 (36)	801 (46)
	PE	40	4.3 (0.9)	5.7 (1.3)
		90	4.5 (1.0)	4.8 (1.0)
		300	3.1 (0.6)	3.3 (0.9)
		900	3.1 (0.6)	4.4 (1.0)
Task 2	RT	40	1016 (34)	1048 (40)
		90	921 (35)	967 (41)
		300	765 (32)	795 (41)
		900	523 (23)	555 (32)
	PE	40	6.0 (1.1)	5.2 (1.0)
		90	5.8 (1.2)	4.9 (0.8)
		300	5.2 (1.0)	4.7 (0.7)
		900	4.8 (1.1)	4.3 (0.7)

Standard errors of the mean in parentheses. SOA, stimulus onset asynchrony.

Task 1 RTs

The ANOVA revealed no significant effect of the main factor stimulus-hand proximity, $F(1,34) = 1.44$, $p = 0.238$, $\eta_p^2 = 0.04$. Also, no main effect was found for the factor SOA, $F < 1$. As well, there was no significant interaction of the factors stimulus-hand proximity and SOA, $F < 1$.

Task 1 PEs

There was no significant main effect of the factor stimulus-hand proximity, $F < 1$. The factor SOA was significant, $F(3,102) = 3.84$, $p = 0.012$, $\eta_p^2 = 0.10$, revealing decreasing PEs with SOA increase. No interaction of stimulus-hand proximity and SOA was found, $F < 1$.

Task 2 RTs

There was no main effect of stimulus-hand proximity, $F(1,34) = 1.97$, $p = 0.170$, $\eta_p^2 = 0.06$. A significant effect for the factor SOA was observed, $F(3,102) = 493.31$, $p < 0.001$, $\eta_p^2 = 0.94$, showing decreasing RTs with SOA increase. However, this effect was not affected by stimulus-hand proximity, $F < 1$.

Task 2 PEs

We found no significant main effect of the factor stimulus-hand proximity, $F < 1$. There was also no effect of the main factor SOA, $F < 1$. Furthermore, no significant interaction of SOA and stimulus-hand proximity was found, $F < 1$.

Discussion

Using a PRP setup that required participants to switch to a color stimulus, we found Task 1 RTs to be unaffected by SOA, whereas Task 2 RTs showed an increase of RTs with decreasing SOA – a typical PRP effect. For PEs, we found a slight increase of error rates at short SOA, which was significant for Task 1 PEs and suggests increased difficulty of dual-task processing at high temporal task overlap. Importantly, this finding was not affected by stimulus-hand proximity. We did not find a modulation of the PRP effect by hand position. Simply put, Task 1–Task 2 switching was not altered in near-hand space. Therefore, our results suggest a robustness of the PRP shifting operation toward modulations of attention and cognitive control induced by the near-hand space. This finding is different to previous work showing that the shift between two different tasks in the task-switching paradigm is optimized in near-hand space (Weidler and Abrams, 2014).

EXPERIMENT 3

In Experiment 3 we performed a third dual-task experiment to investigate the effect of stimulus-hand proximity on Task 1–Task 2 switching using a task setup where Task 1 and Task 2 referred to different features of a single stimulus. It is conceivable that the previous absence of a PRP modulation by stimulus-hand proximity may be due to a frequent feature of dual tasking – the presence of two stimuli that have to be concurrently processed. Instead, in task-switching studies participants often have to switch between different features of a single stimulus. This assumption is supported by the fact

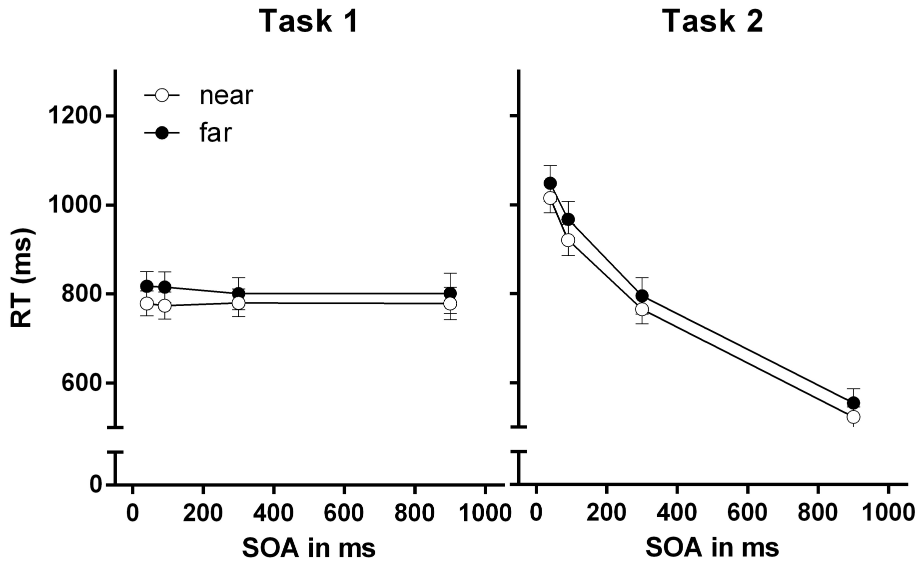

FIGURE 4 | Reaction times for Task 1 and Task 2 for the near-hand and far-hand condition in Experiment 2. Error bars represent standard errors of the mean.

that two judgments concerning two features of one single object are facilitated compared to two judgments concerning two distinct objects (Duncan, 1984). The latter suggests that distinct switching operations have to be performed when processing two dimensions of one single object in close temporal succession compared to processing two distinct objects. Thus, the reduced switch-costs observed in the Weidler and Abrams (2014) experiment may be traced back to the particular feature of using one single bivalent stimulus (i.e., colored geometrical figures) on which two different judgments had to be performed in alternation. In order to adapt the task setup to the study of Weidler and Abrams (2014) while keeping the core logic of a PRP dual task, we used a single bivalent stimulus for Task 1 and Task 2 whereby Task 1–Task 2 switching referred to different features of one single stimulus. To do this, the number stimulus relevant for Task 1 changed its color requiring a color categorization for Task 2, see **Figure 1C**. All predictions were the same as in our previous experiments.

Methods

Participants

A new sample of 35 participants from the University of Münster, Germany (27 female; M_{age} = 24.4 years, SD = 4.3) took part in the experiment. Participants received either course credits or monetary reward. All participants had normal, or corrected-to-normal, vision. All participants were right handed. Written informed consent was provided by all participants prior to their inclusion in the experiment. One participant was excluded from further data analysis due to error rates (M_{total} = 32.81%) exceeding 3 *SD*s of the overall total error rates (M_{total} = 9.56%). The remaining 34 participants were included for further data analysis.

Design

A 2 (Stimulus-hand proximity: near vs. far) × 4 (SOA: 40, 130, 300, and 900 ms) within-subjects repeated measures design was applied.

Stimuli and Apparatus, and Procedure

In Experiment 3, the two tasks used in Experiment 2 were presented centrally on the screen as a single bivalent stimulus. Thereby, Task 1 was identical to Experiments 1 and 2 (number categorization). Task 2 was the same color categorization task as in Experiment 2 (orange vs. blue). Stimulus 1 was presented centrally, and subsequently changed its color thereby initiating Stimulus 2 presentation. The rest of the set-up was identical to Experiment 2. The experiment had a near and far-hand condition, each comprising two blocks. One block contained 64 trials (16 trials per SOA). Thus, 128 trials were performed per stimulus-hand condition, which equals 256 trials in total. The rest of the procedure was identical to Experiment 2.

Results

A repeated measures ANOVA was conducted on RTs and PEs in both tasks. Like in Experiments 1 and 2, within-subject factors were stimulus-hand proximity and SOA. Error trials in either task (9.56%), and trials below 150 ms and above 3000 ms (<0.1%) were excluded from RT data analysis. Double-errors (Task 1 and Task 2 errors) were excluded for Task 2 error analyses (<2%). Greenhouse–Geisser correction was applied in case of violation of sphericity. RTs and PEs are presented in **Table 3**. RTs are further depicted in **Figure 5**.

Task 1 RTs

Neither a main effect for stimulus-hand proximity, $F < 1$, nor for SOA, $F(3,99) = 1.48$, $p = 0.236$, $\eta_p^2 = 0.04$, was found. Moreover, no interaction of both factors was found, $F < 1$.

TABLE 3 | Mean reaction times (RT in ms) and mean errors (PE in %) for Task 1 and Task 2 in Experiment 3.

		SOA	Near	Far
Task 1	RT	40	865 (34)	878 (31)
		90	869 (34)	865 (30)
		300	855 (35)	871 (36)
		900	898 (50)	906 (48)
	PE	40	6.0 (1.0)	6.3 (1.0)
		90	6.9 (1.1)	5.4 (1.1)
		300	4.1 (0.8)	4.2 (1.0)
		900	4.1 (1.1)	3.6 (1.0)
Task 2	RT	40	1129 (35)	1150 (32)
		90	1050 (37)	1043 (32)
		300	874 (37)	889 (38)
		900	593 (28)	606 (29)
	PE	40	3.8 (0.7)	5.4 (0.9)
		90	4.5 (0.8)	3.9 (0.8)
		300	4.0 (0.7)	4.1 (0.6)
		900	5.2 (0.7)	4.9 (0.9)

Standard errors of the mean in parentheses. SOA, stimulus onset asynchrony.

Task 1 PEs

No main effect of stimulus-hand proximity was found, $F < 1$. There was a main effect of SOA, $F(3,99) = 5.61$, $p = 0.003$, $\eta_p^2 = 0.15$, revealing decreasing PEs with SOA increase. There was no interaction of both factors, $F < 1$.

Task 2 RTs

We found no effect of stimulus-hand proximity, $F < 1$. However, we found a main effect for SOA, $F(3,99) = 425.25$, $p < 0.001$, $\eta_p^2 = 0.93$, revealing decreasing RTs with SOA increase. We found no interaction of stimulus-hand proximity and SOA, $F < 1$.

Task 2 PEs

Analysis revealed no main effect of stimulus-hand proximity and SOA, $Fs < 1$. As well, we found no interaction of stimulus-hand proximity and SOA, $F(3,99) = 1.31$, $p = 0.276$, $\eta_p^2 = 0.04$.

Discussion

In Experiment 3 we found evidence for the classic PRP effect when both tasks referred to different features of a single stimulus. Task 2 RTs increased with decreasing SOA between the number presentation and its color change. As expected, Task 1 RTs were unaffected by SOA. Higher Task 1 PEs were found at short SOA indicating increased dual-task difficulty at high task overlap. In Experiment 3, we found no modulation of the PRP effect by stimulus-hand proximity when using a single bivalent stimulus. The Task 1–Task 2 shifting operation was not altered in the near-hand space in an adaptation of the typical PRP paradigm with bivalent stimuli where a shift from number to color information was required. Most importantly, the findings illustrate that Task 1–Task 2 shifting in dual-tasking is unaffected by the near-hand space. Thus, our findings suggest that the shifting process during the PRP paradigm is a relatively rigid processes, which cannot be manipulated via acute changes in attention and cognitive control when two stimuli are processed in near-hand space. The results of Experiment 3 show that the shifting mechanisms involved in the PRP paradigm and the task-switching paradigm have different sensitivities to hand nearness manipulations. This may either be due to different cognitive switching operations required in both paradigms or may be traced back to other more methodological and paradigm-specific differences.

GENERAL DISCUSSION

The aim of this study was to investigate the effect of the near-hand space on between-task switches in three different PRP paradigms.

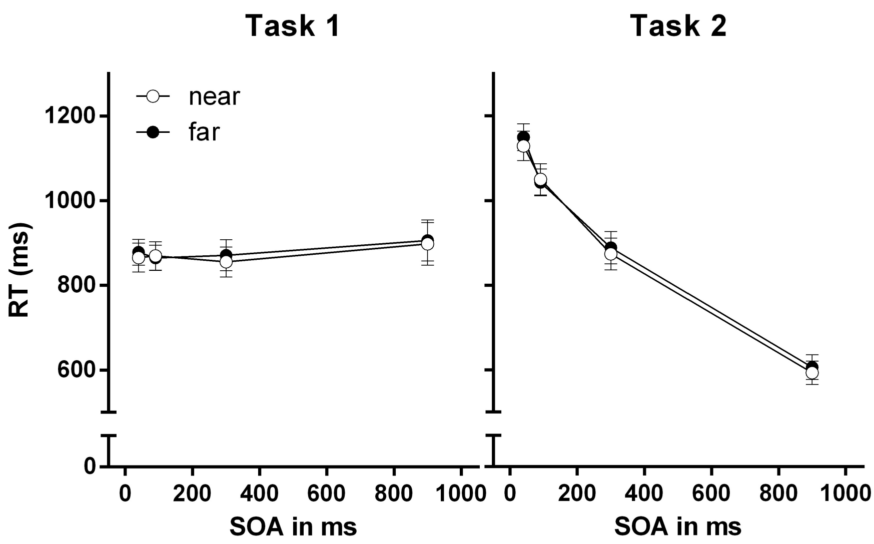

FIGURE 5 | Reaction times for Task 1 and Task 2 for the near-hand and far-hand condition in Experiment 3. Error bars represent standard errors of the mean.

The main finding from the series of three experiments is that the size of the PRP effect did not change with near, compared to far, stimulus-hand proximity. This indicates that the near-hand space did not alter Task 1–Task 2 shifting in the PRP dual-task paradigm. The classic PRP effect in each of the three experiments was shown by deteriorating Task 2 performance at shorter SOA while Task 1 was relatively unaffected by task-overlap.

In Experiment 1, we tested a PRP paradigm that was adapted from the PRP literature (Fischer et al., 2007) in near and far-hand conditions. Specifically, Task 1 was a number categorization task (odd vs. even) and Task 2 was a letter categorization task (vowel vs. consonant). Stimulus 1 and Stimulus 2 presentation was spatially segregated, with Stimulus 1 presented on the right side of the screen and Stimulus 2 presented on the left side of the screen. Based on the available evidence, we hypothesized that near-hand conditions would lead to either prolonged Task 1–Task 2 switching due to delayed attentional disengagement (Abrams et al., 2008) or to improved Task 1–Task 2 switching due to an increased level of cognitive control eliciting an attentional benefit of processing both stimuli (Weidler and Abrams, 2014). The finding that stimulus-hand proximity did not affect Task 1–Task 2 switching was not in line with our predictions and suggests that the switching operation is not altered in the near-hand space in classical dual-tasks. In Experiment 2, we tested the effect of stimulus-hand proximity on Task 1–Task 2 switching, this time using an adapted PRP paradigm where Task 2 was replaced by a color-categorization task, while Task 1 number categorization remained identical to Experiment 1. The finding that Task 1–Task 2 switching was unaffected by stimulus-hand proximity is surprising as previous work has provided evidence for reduced switch costs in a task-switching paradigm that required participants to switch between a form and a color task (Weidler and Abrams, 2014). Our findings may indicate that the switching operation between two distinct and spatially segregated stimuli is not sensitive to near-hand effects. Therefore, in Experiment 3, we integrated Stimulus 1 and Stimulus 2 into a single centrally presented bivalent stimulus manipulating stimulus-hand proximity. Again, we did not observe any effect of stimulus-hand proximity on Task 1–Task 2 switching. Task 1–Task 2 switching was not affected by hand proximity, even when the switching operation had to be performed between two different aspects of a single stimulus rather than between two tasks each referring to a separate stimulus. Thus, again, we were not able to identify an effect of the near-hand space on PRP dual-task performance.

Together, the three experiments reported in this study seem to indicate that between-task switching operations are not affected by the near-hand space. This was apparent during two classic PRP set-ups, in which two distinct stimuli were presented, and during a task set-up in which a single bivalent stimulus had to be processed. Overall, according to our three experiments, it seems very unlikely that the near-hand space does alter Task 1–Task 2 shifting in the PRP paradigm. This is surprising, as previous studies have revealed either delayed attentional disengagement (Abrams et al., 2008) or improved cognitive control (Weidler and Abrams, 2014) in task set-ups that required the switching between two consecutive stimuli (Abrams et al., 2008) or tasks (Weidler and Abrams, 2014). Consequently, shifting operations in the PRP paradigm seem to be relatively rigid and resistant to acute cognitive modulations typically induced by a hand proximity manipulation (Tseng et al., 2012; Brockmole et al., 2013; Abrams et al., 2015). The reduced switch costs reported by Weidler and Abrams (2014) are generally unlikely to reflect altered task preparation costs, as the preparation phase (cue-stimulus interval) was constantly set to 1000 ms in the study of Weidler and Abrams (2014). Rather, the reduced costs may reflect reduced residual switch costs (Monsell, 2003), which have previously been proposed to reflect a structural limitation (Vandierendonck et al., 2010), and have also been proposed for the PRP paradigm (Pashler, 1994). This may also support the assumption that shifting operations in the PRP paradigm are a relatively rigid process in general (Pashler, 1994). The more astonishing it seems that we did not find a reduced PRP effect under hands proximal conditions, which would mimic the findings of reduced switch costs under proximal conditions (Weidler and Abrams, 2014). This suggests that the attentional benefit of processing stimuli in near hand space does not extend to an entire Stimulus 1- Stimulus 2 compound in the PRP paradigm, in which both stimuli appearing in the space between both hands are optimized since we did not find an optimized shifting between both stimuli and tasks.

Another question that arises is, what do these findings tell us about the commonalities and differences between the shifting operations in various dual-task paradigms more generally? The shift in the attentional blink task refers to a switch between two separate stimuli that are presented within a short temporal interval and the stimuli are presented at a single location. As we found no delayed disengagement from processing Stimulus 1 in the near-hand space in none of our experiments, our results clearly contrast the results of Abrams et al. (2008), where the near-hand space induced a slower disengagement from processing Stimulus 1. While switching in the attentional blink task is related to an attention switching between different stimuli, the switching operation in the PRP involves the preparation and switching to an entire new task set involving a much more complex switching operation also including the activation of the new response set. This finding is of particular interest as it has been suggested that similar neural mechanisms may underlie both PRP processing and the attentional blink effect (Marois and Ivanoff, 2005; Marti et al., 2012).

A critical difference between more classical dual tasks (like the PRP paradigm) and task switching is that many task-switching studies use cue-based task switching. The study of Weidler and Abrams (2014) used a form of cue-based switching in which each trial began with a rectangular outline (solid or dashed) that indicated which task had to be performed (i.e., color or shape categorization). The absence of an effect of the near-hand space on PRP dual-task performance in our three experiments may suggest that it might not be the task-switching operation itself that is improved under near-hand conditions. Instead, one could speculate that the observed reduction of task-switching costs under near-hand conditions may be traced back to changes in the processing of the task cue that indirectly affects the size of task switching costs. Near-hand conditions, for example, may have induced a more in-depth cue processing, enhancing the preparation process and leading to reduced task switching costs.

CONCLUSION

Our findings contribute novel and important knowledge to the domain of the near-hand space in multitasking research. We found between-task switches to be unaltered by the near-hand space, indicating that this form of dual-task performance is not altered when hands are located near the stimuli. Mechanistically, it appears that neither a delayed disengagement of attention, nor an enhancement of cognitive control seemed to alter PRP performance. Also, our results suggest that, despite obvious mechanistic similarities between diverse dual-tasking paradigms (Koch et al., 2018), there may at least be some processes that differ substantially between the attentional blink, the task switching paradigm and the PRP paradigm. From thus we conclude that, while a large number of attentional and cognitive effects seem to be sensitive to manipulations of embodied cognition such as our hand proximity manipulation (Reed et al., 2006; Abrams et al., 2008; Gozli et al., 2012; Weidler and Abrams, 2014; Liepelt and Fischer, 2016), we think that it is important to show that some cognitive operations seem to be quite robust and relatively independent of hand proximity. Our findings are not only relevant for basic research on multitasking and the near-hand space, but also for more applied dual-task settings. Our findings suggest that an optimization of task switching in handheld devices may not be easily achieved. However, our findings also indicate that the switching operation between tasks is not disturbed when processing multiple stimuli in the vicinity of our hands in modern handheld devices. Future research should test for effects of hand proximity in multitasking scenarios with various task demands and further levels of attentional control besides those involved in handling cognitive capacity limitations (Pashler, 1994; Meyer and Kieras, 1997). As multitasking involves a diverse set of cognitive control operations representing a multifaceted phenomenon, our results do not exclude alterations of other functions involved in multitasking performance through manipulations of stimulus-hand proximity.

AUTHOR CONTRIBUTIONS

TH wrote the manuscript with the support of RL, RF, and JP. RL and RF designed the experiments. JP carried out the experiments. TH performed the statistical analysis.

FUNDING

This research was supported by the Deutsche Forschungsgemeins chaft (DFG, Grant Nos. LI 2115/2-1 and FI 1624/3-1) in the context of the DFG Priority Program 1772 on "Human performance under multiple cognitive task requirements: From basic mechanisms to optimized task scheduling." We acknowledge support for the Article Processing Charge from the DFG (German Research Foundation, 393148499) and the Open Access Publication Fund of the University of Greifswald.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

REVIEW
published: 29 October 2018
doi: 10.3389/fpsyg.2018.02061

Cognitive-Motor Interference in Neurodegenerative Disease: A Narrative Review and Implications for Clinical Management

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OPEN ACCESS

Edited by:
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Reviewed by:
Hanneke E. Hulst, VU University Medical Center, Netherlands
Francesca Federico, Sapienza Università di Roma, Italy

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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: 02 February 2018
Accepted: 05 October 2018
Published: 29 October 2018

Citation:
McIsaac TL, Fritz NE, Quinn L and Muratori LM (2018) Cognitive-Motor Interference in Neurodegenerative Disease: A Narrative Review and Implications for Clinical Management. Front. Psychol. 9:2061. doi: 10.3389/fpsyg.2018.02061

This paper provides a narrative review of cognitive motor interference in neurodegeneration, including brain imaging findings specific to interference effects in neurodegenerative disease, and dual task assessment and intervention in Parkinson's disease (PD), multiple sclerosis (MS), and Huntington's disease (HD). In a healthy central nervous system the ability to process information is limited. Limitations in capacity to select and attend to inputs influence the ability to prepare and perform multiple tasks. As a result, the system balances demands, switching attention to the most task-relevant information as it becomes available. Limitations may become more apparent in persons with neurodegenerative diseases (ND) with system-specific impairments in PD, MS, and HD. These ND affect both cognitive and motor function and are thus particularly susceptible to dual task interference. Issues related to performer and task characteristics and implications of these findings for both the standard assessment of dual task abilities as well as development and evaluation of interventions aimed at improving dual task ability are discussed. In addition, we address the need for optimizing individualized assessment, intervention and evaluation of dual task function by choosing cognitive and motor tasks and measures that are sensitive to and appropriate for the individual's level of function. Finally, we use current evidence to outline a 5-step process of clinical decision making that uses the dual task taxonomy as a framework for assessment and intervention.

Keywords: multitasking, Parkinson's disease, multiple sclerosis, Huntington's disease, attention

INTRODUCTION

Every day people perform multiple tasks concurrently. Activities like walking and driving while engaged in a discussion require attention to several, sometimes competing actions with shifts and distribution of attention to control movements safely. The ability of the central nervous system to process this information is limited (Marois and Ivanoff, 2005) and influences the nervous system's ability to prepare and perform tasks simultaneously. As a result, the system balances demands, switching attention to the most task-relevant information as it becomes available. Although present in healthy individuals, limitations become more apparent in persons with neurodegenerative disease with system-specific impairments noted in Parkinson's disease (PD) (Dujardin et al., 2013), multiple sclerosis (MS) (Beatty et al., 1995), and Huntington's disease (HD) (Thompson et al., 2010). These ND affect both cognitive and motor function and are thus particularly susceptible to dual task interference. Furthermore, as ND typically are diagnosed in mid- to late-life, the incidence is expected to soar as the population ages and will likely present greater demand for clinical management (Reitz et al., 2011; Reeve et al., 2014).

There is increasing focus on diagnostic approaches, and subsequent intervention development and selection, which are based on addressing motor impairments and resulting activity limitations without compartmentalizing patients primarily on medical diagnoses. For example, the National Institute of Mental Health (NIMH) is defining a new nosology that is based not solely on biology, but also key symptoms across levels of function. Similarly, the American Physical Therapy Association (APTA) is developing diagnoses based on movement system impairments that cut across common medical diagnoses. Indeed, despite etiological differences, many of the neuropathological changes seen in disease such as PD, MS, and HD affect similar processes, including the capacity available for attention to multiple tasks and directly or indirectly executive functioning.

The purpose of this paper is to examine cognitive-motor interference in neurodegenerative diseases (ND) and to discuss similarities across diseases with the aim of developing a common language for identifying dual task impairments. A narrative review of cognitive motor interference in neurodegeneration, including brain imaging findings specific to interference effects in neurodegenerative disease, and dual task assessment and intervention in PD, MS, and HD, serves as the foundation for a novel framework for clinical decision making in this population. Although studies typically focus on only a single ND rather than comparing differences and similarities among several ND, we suggest a need to explore similarities among ND and contrast CMI according to systems-related impairments. Issues related to performer and task characteristics and implications of these findings for both the standard assessment of dual task abilities as well as development and evaluation of interventions aimed at improving dual task ability are discussed.

NEURAL CONNECTIVITY AND COGNITIVE MOTOR INTERFERENCE IN ND

Although dual task deficits have been widely acknowledged in neurodegenerative disease, there is a paucity of knowledge of underlying dual task related connectivity changes. Much of what is known about dual task performance has been drawn from studies of elderly adults. Dual-task performance in the elderly has been associated with activation in the cerebellum (Wu et al., 2013; Blumen et al., 2014), precuneus (Wu et al., 2013; Blumen et al., 2014), superior parietal lobe (Burki et al., 2017), SMA (Blumen et al., 2014), and other prefrontal regions (Blumen et al., 2014; Al-Yahya et al., 2015). In particular, dual task walking has been specifically associated with greater functional connectivity in the SMA and prefrontal regions compared to single task walking in elderly adults on resting state fMRI (Yuan et al., 2015). However, others posit that no distinct brain areas are associated with dual-task performance; rather, performance depends on the interaction of the specific brain areas activated by the individual component tasks (Wantanabe and Funahashi, 2018).

The potential need for activation of multiple cortical areas to achieve optimal dual task performance suggests cortical neural degeneration may relate to specific dual task interference effects. In MS, for example, individuals are more frequently impaired on measures of sustained attention and visuospatial perception, and less frequently impaired on measures of language and immediate and remote memory (Rao et al., 1991). Attention impairment in people with relapsing-remitting MS is related to slowed central processing, including impairment of automatic and controlled processing of information, which may be present in all stages of disease (Balsimelli et al., 2007). Despite weak correlation with disease duration and physical disability status, the degree of cognitive impairment in MS has been related to the extent of topographically specific neuronal tissue damage and loss (Rogers and Panegyres, 2007).

Neuroimaging studies of dual task performance in individuals with PD have shown increased activity compared with controls in the cerebellum, PMC, parietal cortex, precuneus, and prefrontal areas (Wu and Hallett, 2008). Specific regions of the cerebellum, namely the vermis and lobule V, are likely involved with integration of networks associated with motor and cognitive functions. These regions seem to modify the integrated networks for improved efficiency with fewer neural demands to achieve the same performance during dual tasking in healthy participants (Wu et al., 2013; Gao et al., 2017; Leone et al., 2017). In contrast, individuals with PD have increased activity compared with controls in these cerebellar regions for single motor tasks but no additionally activated cerebellar regions during dual task performance (Gao et al., 2017). These findings in PD suggest that the limited cerebellar resources are consumed for single tasks and further activation for dual task performance is unavailable for integrating motor and cognitive networks. Dual task walking is particularly challenging for individuals with PD who experience freezing of gait (FOG) (Spildooren et al., 2010), suggesting that attentional control plays a key role in FOG. Imaging studies demonstrated reduced functional connectivity between the caudate and superior temporal lobe and hypo-connectivity between the dorsal putamen and precuneus that was related to worse dual-task performance (Vervoort et al., 2016). Furthermore, dual-task interference in individuals with FOG was correlated with lateralization of the pedunculopontine nucleus (PPN) structural connectivity (Peterson et al., 2015), supporting the suggestion that the PPN plays a role in attentional control (Yarnall et al., 2011).

In PD, attentional demands may exceed available resources in tasks that depend on internal cues (Brown and Marsden, 1988). Several of the hallmark deficits in PD are due to changes in the frontal-striatal circuits and involve executive defects in planning, initiation, and monitoring of goal-directed behaviors and working-memory. Visuospatial and memory deficits more representative of posterior cortical functioning are also present in persons with PD even without corresponding dementia (Pagonabarraga and Kulisevsky, 2012). In an experiment where motor and cognitive tasks were performed independently and combined in a dual task paradigm, individuals with PD showed distinct striatal recruitment that was not seen in single task performance or in the control participants. Results suggest that individuals with PD may have specific impairments of the cortical-striatal circuitry related to segregation needed to allow independence of motor and cognitive functions during dual tasking (Nieuwhof et al., 2017).

Given the challenge of performing dual tasks in the MRI scanner, fNIRS, EEG, and MEG have been employed to assess neural networks in real time during walking or standing dual tasks. These studies show increased activation in the prefrontal or frontal cortex with dual task walking (Holtzer et al., 2011; Mirelman et al., 2014). Of interest, older adults demonstrated different responses to dual tasks, showing substantial decreases in prefrontal activation compared to young adults (Holtzer et al., 2011; Beurskens et al., 2014). This finding was reproduced in persons with MS; individuals with MS demonstrate greater elevations in prefrontal cortex activation levels during dual-task walking compared to single-task walking than healthy controls (Hernandez et al., 2016). An fMRI study examining cognitive-cognitive dual-tasks in persons with MS found reduced prefrontal and parietal cortical activity that was associated with behavioral performance on tests of attention and executive function (Nebel et al., 2007).

Similar to MS and PD, HD results in motor and cognitive deficits during single task and dual task performance. Selective neuronal death in the cortex and striatum leads to progressive loss of function (Cowan and Raymond, 2006). Although general cognitive changes are seen across the spectrum of HD and may be an early sign of disease (Carlozzi et al., 2011) studies show speed of processing, initiation, and measures of attention may be better able to capture the onset of functional decline in HD (Peavy et al., 2010). Specific impairments in self-generated maintenance of attention may be especially important in the assessment and treatment of multitasking in HD. Problems with simultaneous monitoring of multiple input channels in a divided attention task, set-shifting deficits and the inability to use multimodal information (Sprengelmeyer et al., 1995) suggests that attentional disturbances may be a primary cause of dual task conflicts in HD. Indeed, individuals with HD demonstrate a switching deficit even when the switch is predictable and not time-constrained, indicating a switching deficit distinct from PD and possibly related to executive control default to "response set" (Aron et al., 2003). Imaging studies of neural networks underlying dual task performance are lacking in individuals with HD. One study explored the effect of dual-task walking on EEG parameters in persons with HD and found an increase in the P3 amplitude with walking that was inversely correlated with motor impairment (de Tommaso et al., 2017). These findings suggest that cortical activation was facilitated in a combined motor-cognitive dual task but decreased as motor impairment increased in participants with HD.

To accomplish challenging tasks, including dual tasks, neural networks must flexibly adapt to the demands of the task. Several models of attentional and executive function networks needed for dual task performance have been proposed (Posner and Petersen, 1990; Miyake et al., 2000; McDowd, 2007). The flexible shifting, switching, or division of attention between tasks and the inhibition of information when appropriate leads to successful dual-task performance. The executive control network responsible for allocating attention to task demands has been associated with the prefrontal cortex, anterior cingulate gyrus, other frontal areas (Posner et al., 2006) and parietal areas (Petersen and Posner, 2012), which aligns with neuroimaging work exploring dual tasks in healthy adults.

In the setting of neurodegeneration, there is a loss of neurons within these attention and executive function networks, leading to an overall reduction in the plasticity of the network. A loss in the flexibility of the network to adapt to the demands of challenging dual tasks may explain the impairments seen across ND. There is some evidence of this among individuals with PD, who demonstrate reduced efficiency in neural coding (Wu et al., 2015) as well as greater activation (i.e., greater recruitment of resources) than controls, even when performing automatic tasks (Wu and Hallett, 2005). Reaching a resource ceiling has particular clinical implications for individuals with neurodegenerative disease as they progress through their disease course.

CLINICAL CONSIDERATIONS OF DUAL TASK PERFORMANCE IN ND

Tests and Measures

The effect of performing two tasks simultaneously compared with performance of each task alone is measured as a dual task effect (DTE). Such measurement reveals a cost or benefit to task performance and is an indication of interference or facilitation, respectively, of the limited capacity for attention and information processing. The DTE is a relative measure of an outcome of interest (e.g., gait speed) for each task, with a positive multiplier for variables for which higher values indicate improved performance and a negative multiplier for variables for which higher values indicate worse performance (Kelly et al., 2010). The DTE can be visualized using performance operating characteristic plots that represent the interaction of two tasks and to what degree each task is prioritized relative to the other, a between task trade-off (Kelly et al., 2010).

When assessing dual task function and CMI it is important to choose measures and tasks that are sensitive to specific impairments for that individual. While the inclination for clinicians has been to recognize general categories of impairments according to disease (e.g., bradykinesia and set-switching/attention in PD, dyscoordination and slowed processing speed in MS, hyperkinesia and working memory in HD); the notable heterogeneity of all three diseases and the impairments that are common among them lend support to using systems impairment categories for determining clinical measures and assessment rather than diagnostic criteria. For example, using a serial-7 subtraction task while performing the timed up and go (TUG) task reveals an individual's capability for working memory and attention while walking (Bristow et al., 2016). Alternatively, the Stroop task indicates the ability to selectively inhibit automatic responses in favor of goal-directed ones during functional mobility. Importantly, selection of the appropriate version of the Stroop, visual or auditory, is key to assessing the specific modality impairment of the performer, regardless of medical diagnosis. Performing the walking Trail Making Test (TMT) (Perrochon and Kemoun, 2014) can highlight difficulties in speed of processing (TMT-A) and with mental flexibility and complex attention (TMT-B). Verbal fluency capability can be assessed by timed naming of items (e.g., animals, plants, and foods). Such cognitive tests are influenced by the individual's impairments and by their inherent capabilities and experiences, possibly more than their medical diagnosis.

Measurement of seated dual task activities such as driving, when concerns of balance and gait are eliminated, are primarily limited to driving simulator programs (Campos et al., 2017). While these programs offer assessments of multisensory, multidimensional, and complex task performance in a simulated "real-world" environment, they do not specifically focus on mechanisms of CMI, and are difficult to directly compare results with studies of dual task paradigms in neurorehabilitation. A recently developed measurement for seated dual-task activity, developed for use in people with HD and being tested in PD, is the Moneybox Test (MBT). Subjects transfer coins in order of size, value, and with and without concurrently reciting the alphabet (Clinch et al., 2018). The MBT was shown to be sensitive in early stage HD and may prove useful in identifying CMI when seated using primarily the upper extremities and without the requirement to control standing balance or walking among ND.

Little has been reported on how specific cognitive domains interact with aspects of movement in dual task behaviors, particularly for individuals with ND. However, in a recent study exploring associations between several cognitive domains and gait variability in people with MS, Kalron et al. (2018) found that global cognition, executive function subcategory, and cognitive motor skills were associated with step time variability in non-fallers with MS, but no associations for the fallers. Exploring similar associations in people with PD, Stegemöller et al. (2014) found that cognitive processing speed correlated with stride length and walking speed, and executive function correlated with step width variability. Working memory was not associated with any gait measures. In studies of people with HD, Kloos et al. (2017) found an association between executive function (Stroop Interference and Symbol Digit Modalities Test) and the Tinetti Mobility Test of balance and gait function. Thus, evidence is emerging for a non-diagnosis specific relationship between cognitive and motor functions (e.g., executive function with step variability in MS and PD) and suggesting assessment of dual task function and CMI according to systems impairments may be more relevant clinically.

Among the currently recommended dual task outcome measures is the TUG-Cognitive, a "highly recommended measure" from both the MS and the PD Evidence Database to Guide Effectiveness (MS-EDGE, 2012; PD-EDGE, 2014) of the APTA. Although not measures of dual task *per se*, the Stroop, Symbol Digit Modalities Test, Category Verbal Fluency Test, and the TMT have been recommended and optimized for assessing cognitive function in HD, and the TUG, Tinetti Mobility Test, Four Square Step Test, Berg Balance Scale, and Physical Performance Test for assessing mobility in people with HD (Quinn et al., 2013; Kloos et al., 2014; Stout et al., 2014). Other tests of dual task function that are used clinically, but not specifically recommended for individuals with neurodegenerative disorders, include the Walking and Remembering Test, Stops Walking When Talking test, and the Walking While Talking Test (Beauchet et al., 2009; McCulloch et al., 2009; Fritz et al., 2016).

While dual task training and outcomes related to dual task ability is receiving increasing attention in the literature, significant gaps remain that limit our ability to make concrete clinical recommendations. Importantly, virtually all studies have involved gait and/or balance tasks, and there is a paucity of information pertaining to dual task ability involving upper extremity movements as evaluated by the MBT (Clinch et al., 2018). Ecologically valid outcome measures that reflect dual task abilities are lacking. Gaps in measurement for dual task performance include the lack of longitudinal assessments; lack of exploring relationships of systems impairments, rather than medical diagnoses, and dual task performance; lack of assessments across different motor tasks and across multiple cognitive domains; and few formal assessments to examine the influence of input and output modality on performance. Preliminary studies are underway to ameliorate several of these gaps; long-term screening and assessment of individuals with MS, PD, and HD on a battery of motor, cognitive and dual task measures have been initiated; motor-cognitive dual tasks are being examined in standing, walking, and across multiple cognitive domains; and prospective falls data is being collected by one author to identify relationships among dual-task performance and risk of future falls.

Dual Task Interventions for Neurodegenerative Disease

Over the past 10 years there has been increasing attention to studies that have evaluated interventions to improve dual task ability in individuals with ND. Killane et al. (2015) evaluated community dwelling participants with PD to examine the effect of dual motor-cognitive virtual reality training on dual task performance. Participants completed eight 20-min intervention sessions consisting of a virtual reality maze while performing a cognitive task. A significant improvement was found in dual task cognitive and motor performance, but only for those individuals with PD who experienced freezing of gait. In a systematic review of 21 studies evaluating dual task intervention in individuals with ND, preliminary data supports the use of dual task training for individuals with MS, PD, AD, and dementia (Wajda et al., 2017). The authors categorized dual task interventions into three types: (1) multi-modal exercise interventions, with the underlying tenet that dual task performance could be explicitly improved following direct practice of divided attention; (2) virtual reality and exergaming training, in which participants were immersed in virtual environments which allowed them to encounter objects or characteristics that required attention; and (3) cueing training, in which participants were either provided verbal cues (e.g., to take bigger steps), or were provided with music while walking. A range of different training modalities appear to be beneficial, ranging from simply adding a cognitive task while walking to utilizing virtual reality environments to simulate complex, real-life scenarios that patients may encounter in their day-to-day life.

Despite the positive conclusions above, the recent Duality trial suggests that there is no benefit of dual task training over single task training in people with PD (Strouwen et al., 2017). Significant improvements were reported in dual task gait velocity in both consecutive training and dual task training groups, and the authors suggest that either consecutive or integrated dual task training can be beneficial without increasing fall risk. Similarly, evidence is lacking in support of single versus dual task training in individuals with MS. Monjezi et al. (2017) reported no benefit of dual task training over single task training for balance training with and without a cognitive task. Sosnoff et al. (2017) also reported no clear benefit of dual task versus single task training on gait and balance tasks in a randomized feasibility study in people with MS, although there was a trend for better performance by participants in the dual task training group.

There is some preliminary evidence in support of dual task training's effect on outcomes other than dual task abilities, such as falls. Yitayeh and Teshome (2016) conducted a systematic review to determine the effectiveness of physical therapy interventions to address balance impairment and postural instability in persons with idiopathic PD. The authors reported that training that incorporated both dual tasking and PD-specific balance components significantly benefited balance and gait abilities when compared with usual care. In addition, dual task activities resulted in both a decreased fall rate and fear of falling. Fritz et al. (2015) further reported that dual task training has a range of benefits in individuals with ND. Dual task training was found to improve single task gait velocity and stride length in subjects with PD and AD, and may improve balance and cognition in those with PD and AD. Highly challenging balance training that incorporates dual task training has been shown to be beneficial for individuals with mild to moderate PD compared to usual care (Conradsson et al., 2015). While Fritz et al. (2016) has demonstrated that dual task assessment can be useful in identifying fall risk in HD, there are no papers specifically addressing dual task training in HD.

The presence of a dual task impairment does not immediately suggest that it is amenable to change. Several factors must be considered to facilitate decision-making; these include:

(1) Environmental considerations. If an individual spends a considerable amount of their time in situations where the environment is relatively consistent and non-variable, and their routine has little variability day to day, then the type and degree of dual task training is likely to be different compared to individuals who encounter more day to day variability in their environmental conditions.
(2) Task considerations. Dual tasking may be more important in certain tasks than others. For example, falls risk is known to be increased while performing transitional tasks (e.g., sit to stand) or during certain environment conditions (e.g., low lighting). Therefore, training on dual tasks should be based on a risk assessment and should incorporate activities likely to be encountered.
(3) Performer considerations. The degree of dual task impairment may impact on an individual's ability to benefit from dual task training. If the impairment in either dual tasking or performing either task individually is over a certain threshold it may be best to consider compensatory strategies (e g. avoiding dual task situations altogether). For example, individuals who have significant impairments in cognition (e.g., MMSE below 21) may benefit more from developing compensatory strategies than the time and effort needed to train dual tasks. Furthermore, typical neurodegenerative disease progression involves impairments in learning and re-learning skills. Toward the middle and later stages, when there is typically wide spread cortical and subcortical damage in most ND, learning may be sufficiently impaired to prevent or significantly limit an individual's ability to learn strategies to divide attention in a safe and effective manner.

A Novel Framework for Examining Cognitive Motor Interference in ND

We have previously presented a dual task taxonomy based on a definition of dual tasking as the concurrent performance of two tasks that can be performed independently and have distinct and separate goals (McIsaac et al., 2015). Individual tasks are separated into simple and complex and consideration is given to the degree of task novelty to the performer. Indeed, a highly familiar pairing of two simple tasks, like brushing teeth while watching the news, may be easier for someone to perform than a highly complex single task, like walking across an ice rink. Likewise, "simple" combinations of tasks for one individual, like walking across a crowded street while engaged in a cell-phone conversation, may show little or no interference effects, while the same dual task activity for a person with neurodegenerative disease might be quite impaired. The amount of interference one task has on another scales with the complexity and novelty of the tasks involved. For example, Langhanns and Müller (2017) demonstrated that an instruction to "stay stock-still" during a calculation task required more cortical processing than performing the same cognitive task while sitting or lying down at rest. The explicit instruction to restrict all movement, although not motorically complex, increased the novelty of the sitting task and, therefore, required more cognitive effort for the participants.

For individuals with ND, determining when and how to address dual task impairments should be implemented is a multistep process that starts with the individual and is continually assessed during the disease process. An important factor when considering dual task assessment and intervention is to determine if restorative strategies to improve dual task function are warranted. In some cases, use of compensatory strategies, such as avoidance of complex dual task situations, may be recommended. **Figure 1** provides a schematic of this process using the dual task taxonomy as a framework for assessment and intervention.

Each step of the process takes the status of the individual into consideration, beginning in Step 1 with understanding the patient's values and goals for treatment. From that foundation, clinicians can determine the needs (Step 2) and assess how the patient performs along different levels of the taxonomy (Step 3), noting effects of novelty and complexity on performance. Personalized interventions can be implemented in Step 4 to match the patient goals and target the specific gaps in performance. Importantly, the process continues to re-assessment (Step 5) to emphasize the continued need to monitor and measure changes in performance in neurodegenerative disease as there is rarely a linear benefit from intervention.

The patterns of performance deterioration when a cognitive task and a motor task are simultaneously performed (cognitive-motor interference; CMI) has been previously described (Plummer et al., 2013). Dual task performance may encompass any combination of motor and cognitive tasks, i.e., motor-motor, motor-cognitive, or cognitive-cognitive. In addition to spatial and object-specific considerations, DTEs depend on the pairings of stimuli and response modalities (e.g., visual stimuli requiring tactile response) (Stelzel and Schubert, 2011). These effects may be further defined by dependence (or interdependence) in working memory. As shown in early descriptions of a working memory system, tasks with similar resource demands may create conflicts within separate and/or competing working memory domains with limited resources (see Baddeley, 1986). Hazeltine and Wifall (2011) showed this interaction between sensory modality and working memory in a study demonstrating that vocal responses interfered with working memory for sound while manual responses interfered with working memory for location. Therefore, modality pairings may contribute to dual-task performance

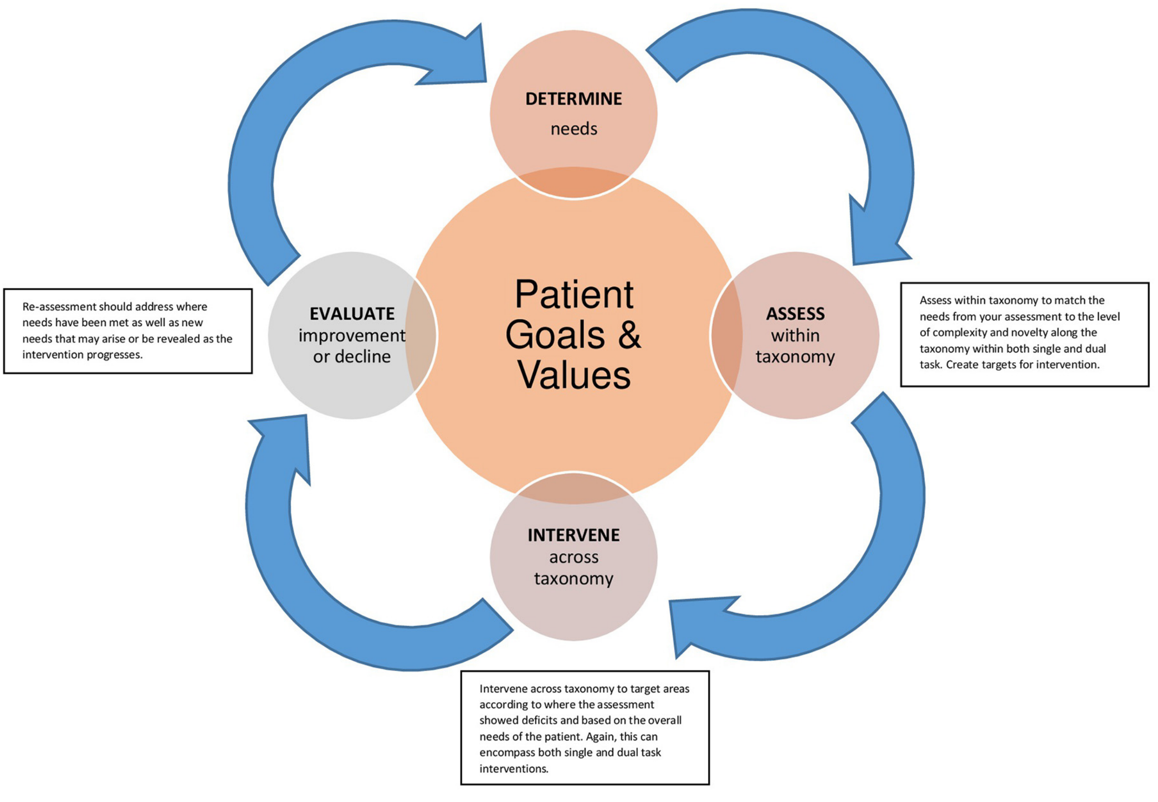

FIGURE 1 | Legend – Framework for assessment and intervention with dual task. The diagram begins in the center with (1) patient goals and values and projects to the clinician's role to (2) determine needs. At point (3) the clinician can match the needs from an assessment to the level of complexity and novelty along the dual task taxonomy to create targets for (4) intervention. (5) Re-assessment should address where needs have been met as well as new needs that may arise or be revealed as the intervention progresses.

by creating further competition for available resources regardless of whether capacity is from single or multiple resources.

The framework highlights the importance of examining components of dual task performance at the level of performer capabilities and task requirements so that areas of potential resource overlap and interference can be appreciated. The framework also provides a common language with which to measure, assess, and deliver interventions for CMI and dual task performance from the perspective of systems-related impairments rather than diagnosis, in line with the development of NIMH's new nosology and the APTA's movement systems diagnoses.

CONCLUSION

The ability to prepare and perform multiple tasks in day to day activity requires the capacity to select, attend to and process information related to the goals for the activity. Limitations in this capacity lead to dual task interference and reduced task performance. The increased difficulty in dual task function for people with ND may be related to system-specific impairments and the pathologic changes in underlying neural networks. The type of tasks paired (motor, cognitive, or both); the specific spatial and object-specific characteristics of the tasks; the postural and gait configurations when carrying out the tasks (seated, standing, and walking); the pairing of modalities used to perceive stimuli and with which to respond (e.g., vision, hearing, and touch) are all considerations in assessing dual task function and developing optimal clinical interventions and rehabilitation strategies. We have reviewed system-specific aspects of motor and cognitive function in MS, PD, and HD and the related underlying neural networks, and summarized possible effects on cognitive motor interference. Optimizing individualized assessment, intervention and evaluation of dual task function requires choosing cognitive and motor tasks and measures that are sensitive to and appropriate for the individual's level of disease and modality involvement. We discuss some measurement tools commonly used for motor, cognitive and dual tasks, but more studies on the psychometric properties of measures of dual task function in ND are needed. The current preliminary evidence from a small number of studies in MS, PD, and HD support the beneficial influence of dual task training, but variability among training methods and lack of standardized incorporation of cognitive tasks into the training protocols leaves limited ability to interpret overall findings. We suggest future research include assessment of similarities among ND and comparisons according to systems impairments instead of medical diagnoses, rather than focusing on a single ND. This has begun to occur in systematic reviews (e.g., Wajda et al., 2017), and we encourage such cross-diagnosis assessments of commonalities in areas from neural networks to dual task performance and intervention. Lastly, we outline a 5-step process of clinical decision making that uses the dual task taxonomy as a framework for assessment and intervention and takes into account the environmental, task, and performer considerations.

AUTHOR CONTRIBUTIONS

TM, NF, LQ, and LM contributed to the conceptualization and writing of this manuscript and agreed to be accountable for all aspects of the work.

FUNDING

TM received funding related to this paper – NIH 1 R15 NS098340-01A1.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 05 October 2018
doi: 10.3389/fpsyg.2018.01153

Influences of Postural Control on Cognitive Control in Task Switching

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The aim of the current study was to investigate the effects of postural control demands on cognitive control processes in concurrent auditory-manual task switching. To this end, two experiments were conducted using an auditory cued task-switching paradigm with different postural control demands (sitting vs. standing). This design allowed us to explore the effect of postural control on switch costs, mixing costs, and the between-task congruency effect. In addition, we varied the cue-based task preparation in Experiment 1 to examine whether preparation processes are independent of additional postural control demands or if the motor control processes required by the postural control demands interfere with task-specific cognitive preparation processes. The results show that we replicated the standard effects in task switching, such as switch costs, mixing costs, and congruency effects in both experiments as well as a preparation-based reduction of these costs in Experiment 1. Importantly, we demonstrated a selective effect of postural control demands in task switching in terms of an increased congruency effect when standing as compared to sitting. This finding suggests that particularly in situations that require keeping two tasks active in parallel, the postural control demands have an influence on the degree to which cognitive control enforces a more serial (shielded) mode or a somewhat less selective attention mode that allows for more parallel processing of concurrently held active task rules.

Keywords: postural control, cognitive control, task switching, task preparation, congruency effect

Edited by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *05 January 2018*
Accepted: *15 June 2018*
Published: *05 October 2018*

Citation:
Stephan DN, Hensen S, Fintor E, Krampe R and Koch I (2018) Influences of Postural Control on Cognitive Control in Task Switching. Front. Psychol. 9:1153. doi: 10.3389/fpsyg.2018.01153

INTRODUCTION

Postural control is crucial in daily life, we depend on it despite the fact that it seems to happen rather effortlessly and automatically. However, studies show significant attentional requirements related to postural control (for a review see Woollacott and Shumway-Cook, 2002) as it refers to the control over a body's position in space for the purpose of balance and orientation (Woollacott and Shumway-Cook, 2002) and requires the dynamic integration of visual, proprioceptive, and vestibular sensory information (Huxhold et al., 2006). Central aspects of postural control research are the influence of individual preconditions such as age (Donker et al., 2007) or proficiency in balance-related skills and abilities (Krampe et al., 2014), and attentional requirements (Woollacott and Shumway-Cook, 2002). Even though postural control seems to be automatic and effortless, it has been shown that even sitting requires a certain amount of postural motor control (Kerr et al., 1985). It has long been presumed that cognition and motor functions share and thus compete for limited attentional resources (Woollacott, 2000).

Attention can be defined as the information processing capacity of an individual, which is presumably limited (see e.g., Kahneman, 1973; Wickens, 1980, 1989). Usually, studies in the context of postural control used so called cognitive-motor dual-tasks (e.g., Dault et al., 2003) to determine the attentional demand. In these cognitive-motor dual-tasks a postural task (e.g., balancing on a balance board, standing, or walking) and a secondary cognitive task (e.g., counting backward; see Yardley et al., 1999) are performed at the same time and performance is compared to performing only one task separately. According to the notion of limited attentional resources, a more demanding postural task should induce more interference with a cognitive tasks and vice versa (Woollacott and Shumway-Cook, 2002; Fraizer and Mitra, 2008; Boisgontier et al., 2013). However, empirical evidence is ambiguous, as some studies report interference between a motor task and a cognitive task (e.g., Andersson et al., 1998), whereas others did not report an effect of postural control demands (whether participants were sitting or standing) on the performance in the cognitive tasks in general (Dault et al., 2001; see also Huxhold et al., 2006). Other studies tackled this issue but the majority focused on the question whether postural control suffers in terms of for example postural sway and sway velocity increases in cognitive-motor dual tasks compared to single tasks (in this case if a cognitive task is added vs. only a postural task is given; see e.g., Beurskens et al., 2016).

An alternative approach that we took in the present study is to investigate the effects of postural control demands on cognitive processing by using a paradigm, which provides a variety of more specific measures of cognitive control and cognitive flexibility. The task-switching paradigm has long been used as a tool to investigate cognitive control (see Koch et al., 2018). In a typical task-switching paradigm, participants have to perform two or more cognitive tasks (e.g., a parity and a magnitude task) in a certain order and either switch from one task to another (i.e., task switch), or repeat the same task (i.e., task repetition). Usually, performance [i.e., response time (RT) and error rate (ER)] is worse in switch trials relative to repetition trials (Monsell, 2003; Kiesel et al., 2010; Vandierendonck et al., 2010, for reviews). This performance decrement was termed switch costs and is considered a marker of transient, trial-to-trial cognitive control processes dedicated to task switching (Grange and Houghton, 2014). Few studies have used task-set switching in multi-tasking paradigms (for exceptions see Brown et al., 2013; Meijer and Krampe, 2018) and whether or not certain switch specific processes are affected by postural control demands has not been explored yet.

Preparation-based reductions of switch costs have been demonstrated in many studies (e.g., Koch, 2001; Monsell, 2003; Kiesel and Hoffmann, 2004; for reviews see Kiesel et al., 2010; Vandierendonck et al., 2010). With regard to the present study, it was of particular interest whether preparation time could be used independently of additional postural control demands or if the cognitive resources necessary to prepare for the upcoming task interfered with the resources occupied by the postural control demands.

Besides switch costs, mixing costs can be assessed by including single-task blocks in the experimental design as a contrast between repetition trial of the mixed-tasks blocks and performance in single task trials (see e.g., Meiran et al., 2000). Usually RTs are higher and ERs are increased in repetition trials in the mixed-tasks blocks compared to in trials in the single-task blocks (see e.g., Rubin and Meiran, 2005). These so-called mixing costs can be interpreted in terms of higher working memory load, due to the effort of updating and maintaining more than one task set (Kiesel et al., 2010), which refers to the cognitive representation of the task requirements (see Monsell, 2003). The maintenance of the task sets is a necessary precondition for parallel processing of both tasks in mixed task blocks and provides basis for crosstalk between both tasks (see e.g., Fischer and Plessow, 2015). However, a previous study found no effect of postural control demands on working memory tasks (Dault et al., 2001), so that it seems important to include mixing costs as a measure of task set maintenance in the current study to investigate the possible influence of postural control on parallel processing.

The task-switching paradigm does not only allow us to study the influence of postural control demands on cognitive processing with regard to cognitive flexibility (i.e., switch costs) and maintenance of concurrent task sets (i.e., mixing costs), but additionally provides the possibility to determine the influence of postural control demands on between-task interference, measured as the between-task congruency effect (Meiran, 2005). In order for congruency effects to occur, bivalent stimuli that can be applied to either task are necessary. If a stimulus requires the same response for both tasks (e.g., a right keypress), it is congruent, while if it requires different responses (e.g., a right keypress in one and a left keypress in the other task), it is incongruent. The congruency effect denotes the finding that usually participants respond faster to congruent compared to incongruent stimuli (Koch and Allport, 2006). Several authors (e.g., Rosenbaum et al., 1986) have suggested a key role of motor programming in accounting for congruency effects. Accordingly, performance benefits in congruent compared to incongruent trials are due to the maintenance of the appropriate motor programming parameter in memory from trial to trial (e.g., if the same finger is used to respond), while motor parameters must be re-programmed in incongruent trials thereby increasing reaction times. Please note, that we take a broader perspective by considering parameters specifying motor programs as part of the task. In order to explain the congruency effect, it has been argued that incongruent stimuli activate both the response according to the currently relevant task rules (i.e., the relevant task set) and the response according to the currently irrelevant task rules (i.e., the irrelevant task set) of the competing task (Kiesel et al., 2010). The congruency effect reflects the inability to shield the currently relevant task set from the currently irrelevant task set (see e.g., Dreisbach and Haider, 2009; Dreisbach and Wenke, 2011). Thus, while efficient task-set shielding should keep both task-sets distinct and prevent interference when alternating between tasks (i.e., decrease the congruency effect), less efficient task-set shielding would cause parallel processing and thus increase competition between tasks and responses arising in incongruent trails. To our knowledge, no study examined task-set shielding, as measured with the congruency effect in the context of postural control.

In sum, our goal was to determine the influence of postural control demands (sitting vs. standing) on switch costs, mixing costs, congruency effect (as a measure of task-set shielding), and the effects of preparation time before switches. To this end, we used a cued task-switching paradigm, in which cues indicated the currently relevant task and in which preparation time can be manipulated by varying the interval between the cue and the stimulus (CSI). Note that in the task-switching literature, the term single task describes the condition in which only one of the two cognitive tasks is performed (in contrast to a mixed condition in which participants alter between both tasks). Thus different from the cognitive-motor dual-task paradigms described earlier, the single task condition in our approach already constitutes a cognitive-motor dual-task, since a cognitive task is performed either in a condition with low (i.e., sitting) or high (i.e., standing) postural control demand.

Our predictions were based on the assumption that coordinating a cognitive task with a sensorimotor task, even a seemingly automatic one like postural control, taxes cognitive control processes and that this interference is pronounced if postural control demands increase. A key feature of our approach is that the switch condition in the task-switching blocks by itself involves several cognitive control operations, which should be most sensitive to interference from a concurrent postural control task, notably the maintenance and change of task sets and shielding operations to prevent between-task crosstalk. Consequentially, we predicted higher switch costs and stronger congruency effects due to reduced shielding in the standing compared with the sitting condition. Finally, given that task preparation has been shown to reduce though not necessarily eliminate switch costs, we assume that all effects of postural control on task-switching performance should be smaller with long preparation interval.

EXPERIMENT 1

Methods

Participants

Thirty-two participants (25 women; mean age = 22.9 years) took part in the experiment. They all had normal or corrected-to-normal hearing acuity, no balance problems and gave informed consent for participation. Information about their sportiveness was collected after the experiment. There were 5 non-sportive and 27 sportive participants (M = 4 h exercise per week since 41 months).

Stimuli, Tasks, and Procedure

In the experiment, participants switched between performing an auditory parity (odd or even) and a magnitude task (smaller or greater than five) while sitting or standing. The spoken number words from one to nine (except five) were presented in German binaurally via headphones (Sennheiser PMX 60; words were recorded in cooperation with the Institute of Technical Acoustics at RWTH Aachen University). In both postural control conditions (sit and stand) participants had to look at a visually presented fixation cross. In the sit condition, it was presented at the center of a 17″ screen (6.5 cm × 6.5 cm) with a viewing distance of approximately 78 cm. In the stand condition, the fixation cross was presented on a white wall (15.6 cm × 15.6 cm) with a viewing distance of 143 cm, while participants stand on a foam mat (1 cm height). Postural control demand was manipulated within participants, and the condition order was counterbalanced across participants. Prior to the experiment, participants were asked to take off their shoes. Furthermore, they were asked to complete a questionnaire before and after the experiment.

The experiment was programmed and presented using SR Research Experiment Builder (SR Research Ltd., Mississauga, ON, Canada). Each trial started with an auditory task cue, which was presented for 200 ms, indicating the relevant task (i.e., a 600 Hz sound cued the parity task; 300 Hz sound cued the magnitude task). The duration of the CSI varied randomly from trial to trial (100 ms vs. 1000 ms). In order to keep the response–stimulus interval (RSI) constant at 1100 ms the response-cue interval (RCI) was 1000 ms in trials with a with short CSI (100 ms) and 100 ms in trials with a long CSI (1000 ms). The number words were presented for 470 ms. The magnitude task asked for a smaller or larger than five decision and the parity task for an odd or even judgment. The response was given via left click for even and greater than five and via a right click for odd or smaller than five on the mouse buttons by using either the left or the right thumb. In both, the sitting and the standing condition, participants held the mouse in both hands in front of the upper body. Please note that we did not counterbalance the stimulus–response (S–R) mappings in both tasks but used the less S–R compatible mappings throughout (defined with respect to the SNARC and MARC effect)[1].

In case of an error, there was an auditory feedback (a twisted 330 Hz sound, created with "Audacity") was presented for 300 ms, delaying the onset of the next cue. The next trial started after a response was made (for an exemplary overview of individual trials, see **Figure 1**).

There were three practice blocks [two single-task blocks (parity and magnitude) à eight trials; one mixed-tasks block à 16 trials] at the beginning, which participants performed while sitting, followed by four experimental blocks in each condition [two single-task blocks (parity and magnitude) with 48 trials; two mixed-tasks blocks with 96 trials]. The task order in the mixed-tasks blocks was randomized for each participant individually (i.e., resulting in 50% task repetition trials and 50% task switch trials). Overall, there were eight experimental blocks (for an exemplary overview see **Figure 2**). The order of experimental blocks as well as the postural control

[1]The SNARC (spatial-numerical association of response codes) effect implies that participants associate small numbers with the left and large numbers with right on a mental number line (Dehaene et al., 1993). The MARC (linguistic markedness of response codes) effect implies that responses are facilitated if stimuli and response codes both have the same (congruent) linguistic markedness (even-right; uneven-left; e.g., Nuerk et al., 2004).

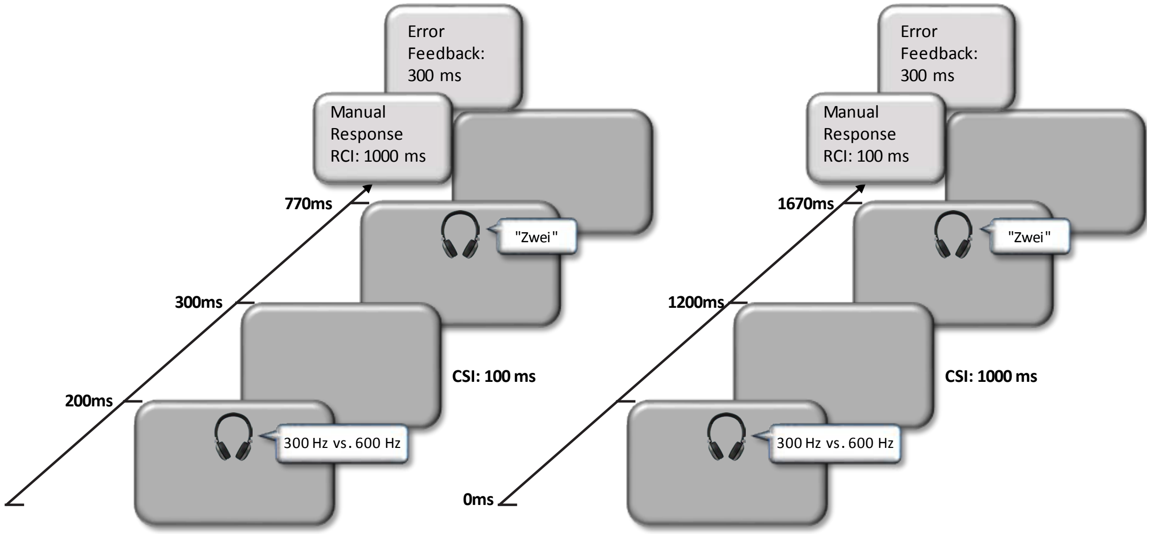

FIGURE 1 | Exemplary overview of trials from the mixed-tasks blocks with either a CSI of 100 ms **(Left)** or a CSI with 1000 ms **(Right)**.

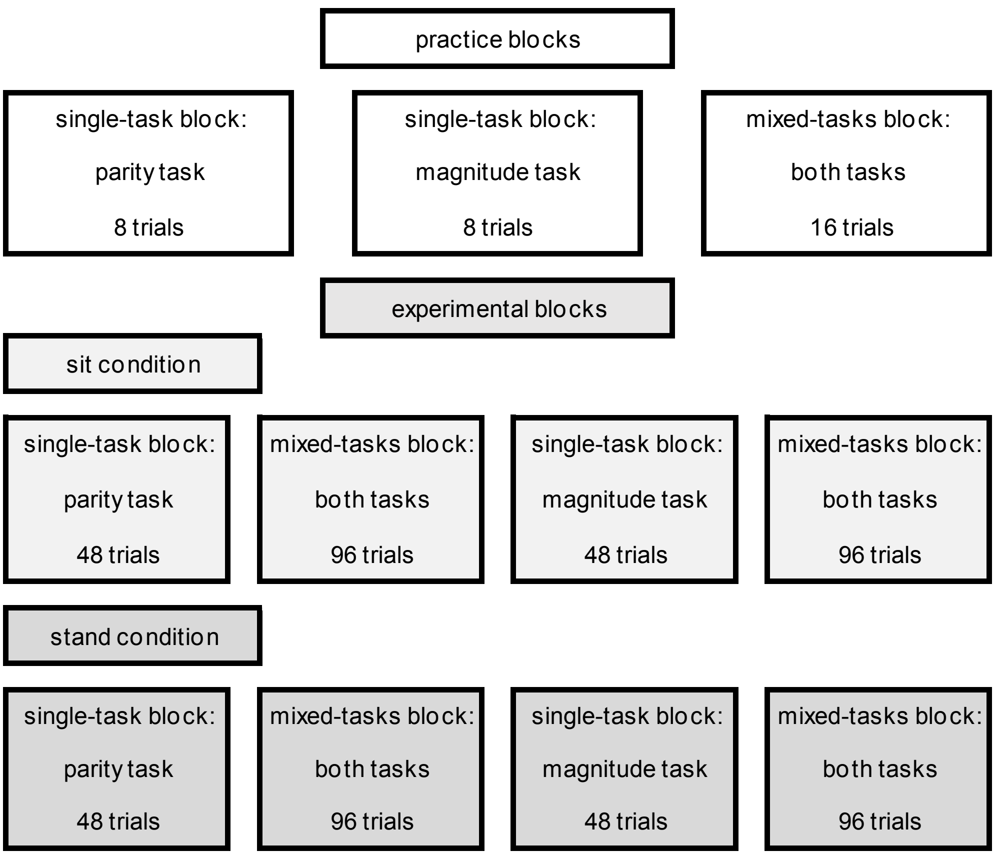

FIGURE 2 | Exemplary overview of the practice and experimental blocks in the sit and stand condition (the order was counterbalanced).

demand was counterbalanced across participants. The practice and experimental blocks were separated by short breaks; the start of each block was initiated via mouse click by the participants. Prior to each block, an instruction containing information about the tasks and the S–R mapping was presented. The experiment lasted about 35 to 40 min.

Design

The independent within-subject variables were postural control (sit vs. stand), congruence (congruent vs. incongruent), CSI (100 ms vs. 1000 ms), transition (switch vs. repetition in the mixed-task blocks), and mixing (single-task blocks vs. repetition in mixed-tasks blocks). The levels of the variables congruence, CSI, and transition varied randomly, whereas the levels of the variables postural control and mixing were blocked. Single-task performance for the parity task and the magnitude task was analyzed separately. Specifically, we analyzed switch costs (switch trials vs. repetition trials in mixed-tasks blocks) and mixing costs (single-task tasks vs. repetition trials in mixed-tasks blocks) separately as two non-orthogonal contrasts. The dependent variables were RT and ER. All tests of significance were conducted at an alpha level of 0.05.

Results

For data analysis, all practice blocks and the first two trials of each block were removed to account for restart costs (cf. Allport and Wylie, 2000). Moreover, all trials exceeding a z-score of $-3/+3$ (z-transformation of all RTs for each participant separately) were discarded as outliers (1.9%). Additionally, for the RT analysis, we excluded all erroneous trials (7.7%), as well as trials after an error. For an overview of the significant results please see **Appendixes A1**, **A2**.

Mixing Costs Analysis

A repeated measure ANOVA with the independent variables postural control (sit vs. stand), congruence (congruent vs. incongruent), mixing (single-task blocks vs. repetition in mixed-tasks blocks), and CSI (100 ms vs. 1000 ms; mean RTs and ERs are presented in **Table 1**) was conducted. For RT, it revealed a significant main effect of postural control [$F(1,31) = 4.39$; $p < 0.05$; $\eta_p^2 = 0.124$], surprisingly, indicating higher RTs in the sit condition (827 ms) than in the stand condition (788 ms). The main effect of congruence was significant, too [$F(1,31) = 42.81$; $p < 0.001$; $\eta_p^2 = 0.580$], indicating higher RTs in incongruent trials (843 ms) compared to congruent trials (772 ms). Furthermore, we found significant mixing costs [$F(1,31) = 55.40$; $p < 0.001$; $\eta_p^2 = 0.641$], indicating higher RTs in repetition trials of mixed-tasks blocks (921 ms) than in single-task blocks (693 ms). Also the main effect of CSI was significant [$F(1,31) = 23.21$; $p < 0.001$; $\eta_p^2 = 0.428$], indicating higher RTs in trials with a CSI of 100 ms (831 ms) compared to trials with a CSI of 1000 ms (784 ms).

Most importantly in the present context, the congruency effect tended to be larger when standing compared to sitting (85 ms vs. 58 ms), as suggested by a non-significant trend for the interaction of postural control and congruence [$F(1,31) = 3.42$; $p = 0.074$; $\eta_p^2 = 0.099$; see **Figure 3**]. Please note that this interaction (i.e., the increased congruency effect in task switching in the standing condition) was significant in Experiment 2. The interaction between congruence and mixing was significant [$F(1,31) = 17.29$; $p < 0.001$; $\eta_p^2 = 0.358$], indicating a larger congruency effect in repetition trials in mixed-tasks blocks compared to single-task blocks (116 ms vs. 26 ms). Also the interaction between CSI and mixing was significant [$F(1,31) = 16.30$; $p < 0.001$; $\eta_p^2 = 0.345$], indicating a larger benefit of preparation in repetition trials in mixed-tasks blocks compared to single-task blocks (89 ms vs. 6 ms). All other interactions were not significant ($F < 1$).

The same ANOVA on ERs (mean RTs and ERs are presented in **Table 1**) showed a significant main effect of congruence [$F(1,31) = 42.73$; $p < 0.001$; $\eta_p^2 = 0.580$], indicating increased ERs in incongruent trials (7.5%) compared to congruent trials (3.1%). Furthermore, we found significant mixing costs, indicating increased ERs in repetition trials in mixed-tasks blocks (6.4%) than in single-task blocks (4.2%). The main effect of postural control and CSI was not significant ($F < 1$).

Also the interaction between congruence and mixing was significant [$F(1,31) = 29.09$; $p < 0.001$; $\eta_p^2 = 0.484$], indicating a larger congruency effect in repetition trials in mixed-tasks blocks compared to single-task blocks (7.5% vs. 1.4%). There was also a non-significant trend toward an interaction between postural control, congruence and CSI [$F(1,31) = 3.10$; $p = 0.088$; $\eta_p^2 = 0.091$], hence numerically the influence of postural control on congruency was larger with a long CSI (congruency effect: 3.1% sitting vs. 5.9% standing) compared to shorter CSI (4.5% sitting vs. 4.2% standing). All other interactions were not significant; for postural control and congruence [$F(1,31) = 1.59$; $p = 0.216$; $\eta_p^2 = 0.049$], for mixing and CSI [$F(1,31) = 1.18$; $p = 0.286$; $\eta_p^2 = 0.037$]; for all other interactions ($F < 1$).

Task-Switching Analysis

A repeated measures ANOVA with the independent variables postural control (sit vs. stand), congruence (congruent vs. incongruent), task transition (switch vs. repetition), and CSI (100 ms vs. 1000 ms) was conducted only using performance in mixed-tasks blocks (mean RTs and ERs are presented in **Table 2**). For RT, it revealed a significant main effect of congruence, indicating longer RTs in incongruent trials (1031 ms) compared to congruent trials [917 ms; $F(1,31) = 34.81$; $p < 0.001$; $\eta_p^2 = 0.529$]. The main effect of transition was significant, too, indicating longer RTs in switch trials (1026 ms) compared to repetition trials [921 ms; $F(1,31) = 50.28$; $p < 0.001$; $\eta_p^2 = 0.619$]. Furthermore, we found a significant main effect of CSI, RTs were significantly longer in trials with a CSI of 100 ms (1038 ms) than in trials with a CSI of 1000 ms [910 ms; $F(1,31) = 80.94$; $p < 0.001$; $\eta_p^2 = 0.723$]. The main effect of postural control was not significant [$F(1,31) = 2.29$; $p = 0.141$; $\eta_p^2 = 0.069$].

Furthermore, the interaction between transition and CSI was significant [$F(1,31) = 19.41$; $p < 0.001$; $\eta_p^2 = 0.385$], indicating higher switch costs in trials with a CSI of 100 ms than in trials with a CSI of 1000 ms (167 ms vs. 89 ms). No other interactions were significant; for postural control and congruence [$F(1,31) = 1.45$; $p = 0.231$; $\eta_p^2 = 0.046$]; for congruence and CSI [$F(1,31) = 1.76$; $p = 0.195$; $\eta_p^2 = 0.054$]; for the four-way interaction between postural control, congruence, CSI, and transition [$F(1,31) = 1.12$; $p = 0.301$; $\eta_p^2 = 0.034$], for all other interactions ($F < 1$).

The same ANOVA on ERs (mean RTs and ERs are presented in **Table 2**) showed a significant main effect of transition [$F(1,31) = 40.92$; $p < 0.001$; $\eta_p^2 = 0.569$], indicating that ERs were higher on switch trials (10.7%) than on repetition trials (6.4%). The main effect of congruence was significant, too

TABLE 1 | RT (ms) and ER (%) (SD in parentheses) data of Experiment 1 for single, repetition, and switch trials as a function of postural control (sit vs. stand), congruence (congruent vs. incongruent and congruence effect), and CSI (100 ms vs. 1000 ms).

		Congruent		Incongruent		Congruence effect		Congruent		Incongruent		Congruence effect	
Condition		100	1000	100	1000	100	1000	100	1000	100	1000	100	1000
Single	Sit	700 (146)	699 (139)	723 (169)	711 (139)	23	12	3.5 (4.6)	4.2 (5.6)	4.9 (5.7)	3.6 (3.5)	1.4	−0.6
	Stand	660 (106)	660 (114)	700 (127)	691 (111)	40	31	3.4 (5.8)	3.0 (4.3)	4.8 (5.0)	6.1 (6.1)	1.4	3.1
Repetition	Sit	945 (300)	848 (223)	1040 (364)	949 (307)	95	101	2.8 (5.1)	2.3 (4.2)	10.4 (8.6)	9.0 (10.2)	7.6	6.7
	Stand	862 (217)	798 (230)	1016 (341)	913 (240)	154	115	3.6 (5.3)	1.9 (3.6)	10.6 (7.6)	10.5 (9.1)	7	8.6
Switch	Sit	1073 (297)	931 (313)	1198 (414)	1005 (323)	125	74	3.9 (5.2)	4.0 (5.3)	16.7 (13.5)	18.3 (13.9)	12.8	14.3
	Stand	1014 (249)	865 (215)	1153 (285)	972 (266)	139	107	5.3 (6.3)	3.0 (4.9)	18.3 (11.6)	16.0 (12.5)	13	13

[$F(1,31) = 74.22$; $p < 0.001$; $\eta_p^2 = 0.705$], indicating higher ERs in incongruent trials (13.7%) than in congruent trials (3.4%). Neither the main effect of postural control ($F < 1$), nor the main effect of CSI [$F(1,31) = 1.85$; $p = 0.184$; $\eta_p^2 = 0.056$] was significant. There was a significant interaction between congruence and transition [$F(1,31) = 17.28$; $p < 0.001$; $\eta_p^2 = 0.358$], indicating larger switch costs in incongruent trials than in congruent trials (7.2% vs. 1.5%). There was also a non-significant trend toward

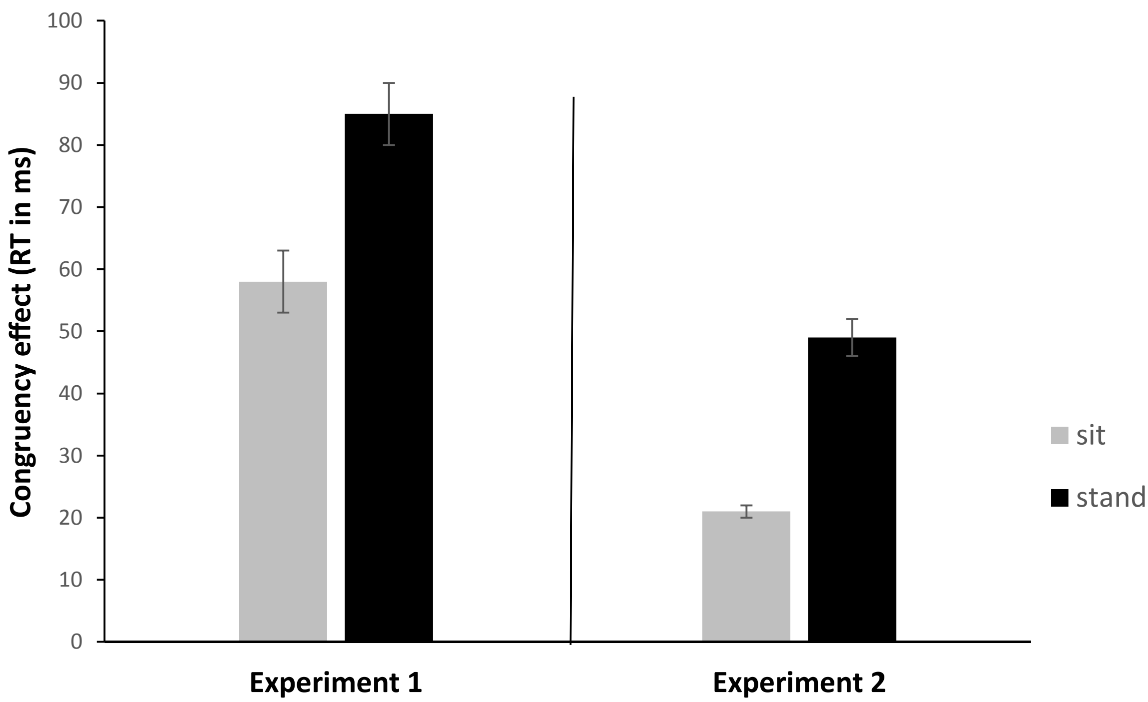

FIGURE 3 | Congruency effect (RT in ms) in Experiment 1 averages across CSIs and Experiment 2 (mixing cost analysis) as a function of postural control (sit vs. stand). Error bars indicate standard deviation.

TABLE 2 | RT (ms) and ER (%) (SD in parentheses) data of Experiment 2 for single, repetition, and switch trials as a function of postural control (sit vs. stand) and congruence (congruent vs. incongruent and congruence effect).

Condition		Congruent	Incongruent	Congruence effect	Congruent	Incongruent	Congruence effect
Single	Sit	688 (111)	701 (114)	13	4.1 (4.3)	4.1 (3.9)	0
	Stand	674 (109)	698 (120)	24	3.9 (6.0)	3.5 (3.8)	−0.4
Repetition	Sit	939 (245)	969 (244)	30	3.1 (4.3)	7.7 (6.7)	4.6
	Stand	926 (236)	1000 (255)	74	3.7 (4.1)	7.4 (5.8)	3.7
Switch	Sit	1124 (298)	1177 (305)	53	5.2 (5.9)	12.1 (6.9)	6.9
	Stand	1098 (306)	1180 (380)	82	4.9 (6.2)	15.8 (11.9)	10.9

an interaction between postural control, transition, and CSI [$F(1,31) = 3.30$; $p = 0.079$; $\eta_p^2 = 0.096$], hence numerically with a short CSI switch costs were smaller when sitting compared to standing (switch costs: 3.7% sitting vs. 4.7% standing) the pattern was reversed with a long CSI (switch costs: 5.6% sitting vs. 3.3% standing). All other interactions were non-significant; for postural control and CSI [$F(1,31) = 2.78$; $p = 0.105$; $\eta_p^2 = 0.082$]; for postural control, congruence, transition and CSI [$F(1,31) = 1.54$; $p = 0.225$; $\eta_p^2 = 0.047$]; for all other interactions ($F < 1$).

Discussion

In Experiment 1, we found significant switch costs, mixing costs, and a congruency effect in RTs and ER. Furthermore, an effect of preparation was present in terms of shorter RTs on trials with a long CSI compared to trials with a short CSI as well as reduced switch and mixing costs on trials with a long CSI compared to trials with short CSI. With regard to the influence of postural control demands, there was a non-significant numerical trend depicting faster responses when standing compared to sitting. However, there was no other interaction between CSI and postural control, so it does not seem that the benefit of preparation is affected by postural control demands. Further, neither the interaction between postural control and task transition nor between postural control and mixing was significant, thus the postural control demand does not seem to directly affect switch costs or mixing costs.

Importantly, even though the interaction between postural control and congruency failed to reach significance by a slight margin, there was a numerical trend regarding a larger congruency effect when standing compared to sitting. In order to follow up this effect, a second experiment was conducted in which we used a constant CSI of medium duration (400 ms).

EXPERIMENT 2

Methods

Participants

Twenty-four participants (21 women; mean age = 23.3 years) took part in the experiment. They all had normal or corrected-to-normal hearing acuity, no balance problems and gave informed consent for participation. They received course credits for participation. Information about the sportiness were collected after the experiment. There were 2 non-sportive and 22 sportive participants ($M = 5$ h exercise per week since 115 months).

Stimuli, Tasks, Procedure, and Design

Stimuli, tasks, and procedures in Experiment 2 were identical to Experiment 1, the only difference being, that the CSI was held constant at 400 ms. The independent within-subject variables were postural control (sit vs. stand), congruence (congruent vs. incongruent), transition (switch vs. repetition), and mixing (single-task blocks vs. repetition trials in mixed-tasks blocks). Data analyses proceeded as in Experiment 1.

Results

All practice blocks and the first two trials of each experimental block were discarded for all analyses. Moreover, we excluded all outliers by performing z-transformations of all RTs for each participant separately. Trials with a z-score of $-3/+3$ were discarded as outliers (1.8%). Additionally, for the RT analysis, we excluded all erroneous trials (6.8%), as well as trials following errors. For an overview of significant results please see **Appendixes A3**, **A4**.

Mixing Costs Analysis

A repeated measure ANOVA with the independent variables postural control (sit vs. stand), congruence (congruent vs. incongruent), and mixing (single-task blocks vs. mixed-tasks blocks), only using performance of single-task block and the repetition trials from the mixed-tasks blocks (mean RTs and ERs are presented in **Table 2**) was conducted. As in Experiment 1, it showed a significant main effect congruence, indicating higher RTs in incongruent trials (842 ms) compared to congruent trials {807 ms; [$F(1,23) = 14.36$; $p = 0.001$; $\eta_p^2 = 0.384$], and of mixing [$F(1,23) = 64.42$; $p < 0.001$; $\eta_p^2 = 0.737$]}, indicating higher RTs in mixed-tasks blocks (958 ms) than in single-task blocks (690 ms). The main effect of postural control was not significant ($F < 1$).

Most importantly, we found a significant interaction between postural control and congruence [$F(1,23) = 6.08$; $p < 0.005$; $\eta_p^2 = 0.209$]. This interaction indicates a larger congruency effect when standing (49 ms) compared to sitting (21 ms) and thus replicates the almost significant trend ($p = 0.074$) that we observed in Experiment 1 (85 ms vs. 58 ms; see **Figure 3**).

Also, the interaction between congruence and mixing was significant [$F(1,23) = 4.73$; $p < 0.005$; $\eta_p^2 = 0.170$], indicating a larger congruency effect in mixed-tasks (51 ms) compared to single-task blocks (18 ms). No other interaction was significant; for postural control, congruence, and mixing [$F(1,23) = 1.04$; $p = 0.318$; $\eta_p^2 = 0.043$], for all other ($F < 1$).

As in Experiment 1, the same ANOVA on ERs showed a significant main effect of congruence [$F(1,23) = 10.02$; $p < 0.05$; $\eta_p^2 = 0.303$], indicating increased ERs in incongruent (5.7%) compared to congruent trials (3.7%), of mixing [$F(1,23) = 12.16$; $p < 0.05$; $\eta_p^2 = 0.346$], indicating increased ERs in mixed-tasks blocks (5.5%) than in single-task block {3.9%, and the interaction [$F(1,23) = 17.23$; $p < 0.001$; $\eta_p^2 = 0.428$]}, indicating a larger congruency effect in mixed-tasks blocks (4.2%) compared to single-task blocks (−0.2%). No other effect or interaction was significant ($F < 1$).

In sum, in the mixing-costs analysis of Experiment 2, the main effects demonstrated in Experiment 1 were nicely replicated. Importantly, the numerical trend toward an interaction between postural control and congruency in mixing costs could be replicated in RTs, thus providing converging evidence for an influence of postural control demands.

Task-Switching Analysis

A repeated measures ANOVA with the independent variables postural control (sit vs. stand), congruence (congruent vs. incongruent) and transition (switch vs. repetition), only using performance of mixed-tasks blocks (mean RTs and ERs are presented in **Table 2**) was conducted. For RT, as in Experiment 1, it showed a significant main effect of congruence, indicating longer RTs in incongruent trials (1081 ms) compared to congruent trials [1022 ms; $F(1,23) = 9.65$; $p < 0.05$; $\eta^2_p = 0.296$] and a significant main effect of transition, indicating longer RTs in switch trials (1145 ms) compared to repetition trials [958 ms; $F(1,23) = 32.09$; $p < 0.001$; $\eta^2_p = 0.582$]. The main effect of postural control was not significant ($F < 1$).

Like in the mixing-costs analysis, we found a significant interaction between postural control and congruence [$F(1,23) = 5.37$; $p < 0.05$; $\eta^2_p = 0.189$], indicating a larger congruency effect when standing (78 ms) compared to sitting (41 ms). Please note that this interaction was not present in Experiment 1. No other interaction was significant ($F < 1$).

The same ANOVA on ERs replicated the main effects and interaction demonstrated in Experiment 1: we found a main effect of congruence [$F(1,23) = 39.40$; $p < 0.001$; $\eta^2_p = 0.631$], indicating increased ERs in incongruent trials (10.8%) compared to congruent trials (4.2%), a main effect of transition [$F(1,23) = 57.63$; $p < 0.001$; $\eta^2_p = 0.715$], indicating increased ERs in switch (9.5%) compared with repetition trials (5.5%), and an interaction between congruence and transition [$F(1,23) = 15.82$; $p = 0.001$; $\eta^2_p = 0.408$], reflecting larger congruency effects in switch (6.4%) compared with repetition trials (1.6%).

The main effect of postural control was not significant ($F < 1$), but the interaction between postural control, congruence, and transition was significant [$F(1,23) = 7.17$; $p < 0.05$; $\eta^2_p = 0.238$]. A follow-up two-way ANOVA, conducted separately for repetition and switch trials showed that, while for switch trials, there was a non-significant numerical trend toward an interaction between postural control and congruence [$F(1,23) = 3.27$; $p = 0.084$; $\eta^2_p = 0.124$], suggesting a larger congruency effect while sitting (4.6%) compared to standing (3.7%) this trend was not present for the repetition trials ($F < 1$).

GENERAL DISCUSSION

The aim of the current study was to investigate the effects of postural control demands on cognitive control processes in concurrent cognitive task switching. To this end, we combined an auditory cued task-switching paradigm with manual responses with different postural control demands (sitting vs. standing). This design allowed us to explore the effect of postural control on specific component processes of cognitive control, namely switch costs, mixing costs, and the between-task congruency effect. In addition, we were interested to see whether cue-based task preparation processes are independent of additional postural control demands or if the motor control processes required by the postural control demands interfere with task-specific cognitive preparation processes.

We replicated the standard effects in task switching, such as switch costs, mixing costs, and congruency effects in both experiments (for reviews see Kiesel et al., 2010; Vandierendonck et al., 2010; Koch et al., 2018). The main difference between Experiment 1 and Experiment 2 was the manipulation of preparation time (CSI). We demonstrated the expected influence of CSI including preparation-based reduction of switch and mixing costs. At the same time, these effects appeared to be independent of our postural control manipulation. For the remainder of the discussion, we focus on the effects of postural control demands on cognitive control processes in single- and switching tasks.

In both experiments, the effects of a concurrent postural control task on single-task performance (i.e., in pure blocks of the parity task alone or the magnitude task alone) and performance in mixed tasks blocks did not differ between sitting and standing conditions. We did not find an influence of postural control on mixing costs suggesting that increased postural control demands while standing do not interfere with the working-memory maintenance of the task set in task-repetition trials in mixed blocks. This finding is in line with the study of Dault et al. (2001) who found no costs in WM performance. Further, we did not find a significant influence of postural control on specific task-switch costs, suggesting that increasing postural control demands do not lead to additional interference with the processes underlying an instructed switch of tasks over and above what we demonstrated for mixing costs.

Note, however, that this conclusion is limited to performance in the auditory task-switching paradigm, because we did not assess potential costs in postural control. The most prominent effect in our view relates to the effects of increased postural control demands on task set shielding assessed through the congruency effect. In mixed-task blocks, the congruency effect was numerically larger compared to the single task blocks, and congruency was increased while standing as compared to sitting. This effect on the size of the congruency effect differed across experiments and type of analyses slightly, but the overall direction of this influence of postural control was consistent. Note that even though there was a congruency effect in single tasks, it did not differ with postural control demands in this condition.

As described earlier, the congruency effect is a measure for between-task interference (Meiran, 2005). If participants alternate between two tasks, they must keep task sets and rules distinct enough to prevent interference. Several authors have argued for a shielding function that protects from interference and helps focusing attention on the relevant task by increasing selectivity of processing (e.g., Dreisbach and Haider, 2008, 2009). In incongruent trials, the irrelevant stimulus feature can activate a competing response instantiating the currently irrelevant S–R rule, which creates task interference that has to be resolved (Kiesel et al., 2010). Better task set shielding should keep the congruency effect small. Conversely, less efficient task-set shielding would increase the degree of parallel processing and thus the degree of task and response competition that arises on incongruent trials. Our findings suggest that shielding is less efficient when task sets need to be switched in the mixed blocks, in particularly if cognitive control processes are already occupied by a concurrent postural control task. From a slightly different perspective, one might argue that the main difference between single tasks and mixed tasks is that tasks are processed strictly serially in single task blocks and only one task set is necessary to perform the task successfully. In contrast, both task sets need to be kept active in the mixed tasks blocks, so tasks can be processed, to some degree, in parallel (see also Fischer and Plessow, 2015). If this situation is aggravated by increased concurrent postural control demands (i.e., standing relative to sitting), shielding might become more difficult. In the context of the present study, we demonstrated that particularly in this situation, implying a parallel processing of both tasks, there is an influence of postural control demands. At a more general level, this provides evidence that motor control demands influence the degree of task-set shielding and thus demonstrate that motor control and cognitive control in task switching are not independent but interact with each other.

Besides mixing costs, switch costs, as a measure of cognitive flexibility, were assessed (Kiesel et al., 2010; Vandierendonck et al., 2010, for reviews). We found that switch costs were substantial, but that they are not affected by the postural control demand (see also Dault et al., 2001). This suggests that the task switch itself, that is, the encoding of new instruction and the change of the currently relevant task rules refers to a set of processes that are unrelated to motor control in the sense that they function independently of whether participants are generally in a mode that encourages a more serial or more parallel processing mode (i.e., more or less shielded task sets). It is also noteworthy that overall performance level was not affected by postural control demands, suggesting that these demands have a highly specific influence on a subset of cognitive control processes, notably a cognitive control parameter that specifies the degree to which parallel processing is allowed (Woollacott and Shumway-Cook, 2002, for a review). This finding thus adds to a growing number of findings suggesting that the degree of serial vs. parallel processing in multitasking is not structurally determined but can vary with contextual factors (Fischer and Plessow, 2015).

CONCLUSION

In conclusion, the present study demonstrated an effect of postural control demands in task switching in terms of an increased congruency effect. It seems that particularly in situations that require keeping two tasks active in parallel, the postural control demands have an influence on the degree to which cognitive control enforces a more serial (shielded) mode or a somewhat less selective attention mode that allows for more parallel processing of concurrently held active task rules. Future work is desirable to explore how exactly the difference of postural control in standing vs. sitting translates into this specific bias to process tasks less serially when standing.

ETHICS STATEMENT

This study was carried out in accordance with the ethical guidelines of the German Psychological Society (Deutsche Gesellschaft für Psychologie) with written informed consent from all subjects. Ethical review and approval was not required for this study in accordance with the national and institutional guidelines. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

AUTHOR CONTRIBUTIONS

DS developed the idea together with IK and frequently discussed it with RK, SH, and EF. DS wrote the manuscript, while IK, RK, SH, and EF contributed by giving feedback to improve the manuscript. SH also tested the participants of Experiment 1 and programmed the experiments.

FUNDING

This research was funded by the DFG (Deutsche Forschungsgemeinschaft; priority program SPP 1772: Grant KO 2045/19-1).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

TABLE A1 | An overview of the significant results of the mixing costs analyses in Experiment 1.

		Experiment 1
		Mixing costs analysis
Postural control	RT	$F(1,31) = 4.39$; $p < 0.05$; $\eta_p^2 = 0.124$
Congruence	RT	$F(1,31) = 42.81$; $p < 0.001$; $\eta_p^2 = 0.580$
	ER	$F(1,31) = 42.73$; $p < 0.001$; $\eta_p^2 = 0.580$
Mixing	RT	$F(1,31) = 55.40$; $p < 0.001$; $\eta_p^2 = 0.641$
	ER	$F(1,31) = 14.88$; $p = 0.001$; $\eta_p^2 = 0.324$
CSI	RT	$F(1,31) = 23.21$; $p < 0.001$; $\eta_p^2 = 0.428$
Postural control × congruence	RT	$F(1,31) = 3.42$; $p = 0.074$; $\eta_p^2 = 0.099$
Congruence × mixing	RT	$F(1,31) = 17.29$; $p < 0.001$; $\eta_p^2 = 0.358$
	ER	$F(1,31) = 29.09$; $p < 0.001$; $\eta_p^2 = 0.484$
CSI × mixing	RT	$F(1,31) = 16.30$; $p < 0.001$; $\eta_p^2 = 0.345$

TABLE A2 | An overview of the significant results of the task-switching analyses in Experiment 1.

		Experiment 1
		Task-switching analysis
Congruence	RT	$F(1,31) = 34.81$; $p < 0.001$; $\eta_p^2 = 0.529$
	ER	$F(1,31) = 74.22$; $p < 0.001$; $\eta_p^2 = 0.705$
Transition	RT	$F(1,31) = 50.28$; $p < 0.001$; $\eta_p^2 = 0.619$
	ER	$F(1,31) = 40.92$; $p < 0.001$; $\eta_p^2 = 0.569$
CSI	RT	$F(1,31) = 80.94$; $p < 0.001$; $\eta_p^2 = 0.723$
Transition × CSI	RT	$F(1,31) = 19.41$; $p < 0.001$; $\eta_p^2 = 0.385$
Congruence × transition	ER	$F(1,31) = 17.28$; $p < 0.001$; $\eta_p^2 = 0.358$

TABLE A3 | An overview of the significant results of the mixing costs analyses in Experiment 2.

		Experiment 2
		Mixing costs analysis
Congruence	RT	$F(1,23) = 14.36$; $p = 0.001$; $\eta_p^2 = 0.384$
	ER	$F(1,23) = 10.02$; $p < 0.05$; $\eta_p^2 = 0.303$
Mixing	RT	$F(1,23) = 64.42$; $p < 0.001$; $\eta_p^2 = 0.737$
	ER	$F(1,23) = 12.16$; $p < 0.05$; $\eta_p^2 = 0.346$
Postural control × congruence	RT	$F(1,23) = 6.08$; $p < 0.005$; $\eta_p^2 = 0.209$
Congruence × mixing	RT	$F(1,23) = 4.73$; $p < 0.005$; $\eta_p^2 = 0.170$
	ER	$F(1,23) = 17.23$; $p < 0.001$; $\eta_p^2 = 0.428$

TABLE A4 | An overview of the significant results of the task-switching analyses in Experiment 2.

		Experiment 2
		Task switching analysis
Congruence	RT	$F(1,23) = 9.65$; $p < 0.05$; $\eta_p^2 = 0.296$
	ER	$F(1,23) = 39.40$; $p < 0.001$; $\eta_p^2 = 0.631$
Transition	RT	$F(1,23) = 32.09$; $p < 0.001$; $\eta_p^2 = 0.582$
	ER	$F(1,23) = 57.63$; $p < 0.001$; $\eta_p^2 = 0.715$
Postural control × congruence	RT	$F(1,23) = 5.37$; $p < 0.05$; $\eta_p^2 = 0.189$
Congruence × transition	ER	$F(1,23) = 15.82$; $p = 0.001$; $\eta_p^2 = 0.408$
Postural control × congruence × transition	ER	$F(1,23) = 7.17$; $p < 0.05$; $\eta_p^2 = 0.238$

frontiers in Psychology

ORIGINAL RESEARCH
published: 07 August 2018
doi: 10.3389/fpsyg.2018.01375

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Tapping the Full Potential? Jumping Performance of Volleyball Athletes in Game-Like Situations

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Background: One key issue in elite interactive team sports is the simultaneous execution of motor actions (e.g., dribbling a ball) and perceptual-cognitive tasks (e.g., visually scanning the environment for action choices). In volleyball, one typical situation is to prepare and execute maximal block jumps after multiple-options decision-making and concurrent visual tracking of the ongoing game dynamics to find an optimal blocking location. Based on resource-related dual- and multi-tasking theories simultaneous execution of visual-cognitive and motor tasks may interfere with each other. Therefore, the aim of this study was to investigate whether volleyball-specific perceptual-cognitive demands (i.e., divided attention, decision making) affect blocking performance (i.e., jumping performance and length of the first step after the ready-block-position) compared to relatively isolated jumping performance.

Methods: Twenty-two elite volleyball players (1st – 3rd German league) performed block jumps in front of a net construction in a single-task condition (ST) and in two perceptual (-cognitive) dual-task conditions including a dual-task low (DT_L; presenting a picture of an opponent attack on a screen) and a dual-task high condition (DT_H; presenting videos of an offensive volleyball set play with a two-alternative choice).

Results: The results of repeated-measures ANOVAs showed a significant effect of conditions on jumping performance [$F(2,42) = 33.64$, $p < 0.001$, $\eta_p^2 = 0.62$] and on the length of the first step after the ready-block-position [$F(2,42) = 7.90$, $p = 0.001$, $\eta_p^2 = 0.27$). *Post hoc* comparisons showed that jumping performance in DT_H ($p < 0.001$) and DT_L ($p < 0.001$) was significantly lower than in ST. Also, length of the first step after the ready-block-position in DT_H ($p = 0.005$) and DT_L ($p = 0.028$) was significantly shorter than in ST.

Conclusion: Our findings suggest that blocking performance (i.e., jumping height, length of the first step) decreases in elite volleyball players when a perceptual (-cognitive) load is added. Based on the theory of Wickens (2002), this suggests a resource overlap between visual-processing demands for motor performance and for tracking the dynamics of the game. Interference with the consequence of dual-task related performance costs can therefore also be found in elite athletes in their specific motor expert domain.

Keywords: dual-task, cognitive-motor interference, block jumping, elite sports, perceptual-cognitive expertise, volleyball

OPEN ACCESS

Edited by:
Pierre-Paul Vidal, Université Paris Descartes, France

Reviewed by:
Stefan Künzell, University of Augsburg, Germany
Florian Loffing, University of Oldenburg, Germany

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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *02 March 2018*
Accepted: *16 July 2018*
Published: *07 August 2018*

Citation:
Fleddermann M-T and Zentgraf K (2018) Tapping the Full Potential? Jumping Performance of Volleyball Athletes in Game-Like Situations. Front. Psychol. 9:1375. doi: 10.3389/fpsyg.2018.01375

INTRODUCTION

In interactive team sports, athletes act in complex and dynamic environments, with the player itself, balls, teammates, opponents, referees, and sometimes the coach and the spectators moving in space with periodic changes in situational requirements such as attacking or defending (Gréhaigne et al., 2005; Lennartsson et al., 2014). In this context, perceptual-cognitive demands need to be processed concurrently to motor execution such as running, dribbling, or passing the ball. In elite volleyball, players not only have to spike or pass the ball at a specific spatial location, they also, in a preparatory manner, have to transport their bodies to the spot where the adequate technique has to be executed. Major parts of practice are allocated to improve these technical details related to anticipatory leg/foot work and ball contact skills in isolation from tactical demands (Gabbett et al., 2006). This is true for receiving, spiking, blocking, or defending (Gabbett et al., 2006; Katic et al., 2006). During competition or in game-like practice situations, however, these techniques are combined with visual-tactical requirements such as monitoring ball and opponents' trajectories, decision-making for blocking or defending positions or for setting locations for the counterattack. One success-oriented goal for the attacking team is to "move" the opponent blockers in the wrong direction along the net, i.e., for the setter to pass the ball at a position remote from the initial position of the opponent blockers (Gasse, 1995; Gonzalez-Silva et al., 2016). Therefore, a typical situation for a blocker is to be aware of the number and position of the opponent attackers, to shortly observe the ball trajectory after reception, to position adequately for the upcoming attack by performing preparatory block steps along the net, to concurrently observe the attackers approach direction and to then timely jump maximally for reaching the hands over the net toward the ball with the aim to block the ball or at least to slow down the ball to facilitate defense by a teammate (Westphal and Gasse, 1985; Gasse, 1995; Afonso et al., 2005; Ficklin et al., 2014).

In ball sports, obviously, with its dynamic nature, execution of motor skills is inevitably linked to and needs to be adapted to perceptual-cognitive requirements. Nevertheless, expert players seem to perform these motor skills effortlessly. Fitts and Posner (1967) declared this stage as the "autonomous" stage, where movements are consistent and presumably require no or little cognitive control, so that attention may be focused on tactical choices. In the dual-task literature, a great number of studies has focused on the attentional requirements for motor and perceptual-cognitive tasks and their integration as the capacity to process several streams of information in parallel seems to be restricted (for an overview, see Woollacott and Shumway-Cook, 2002; Yogev-Seligmann et al., 2008; Al-Yahya et al., 2011; Krasovsky et al., 2017; Leone et al., 2017). Many studies suggest that some attentional resources are essential to integrate sensory (visual, vestibular, tactile, proprioceptive, acoustic, etc.) (re-)afferences and motor efferences (Dietrich, 2006; Hamacher et al., 2015; Krasovsky et al., 2017). Conceptual ideas explain performance decrements by a structural limitation of capacities (e.g., Pashler, 1994, 2000) or by limited multiple resource pools (Wickens, 2002, 2008). The multiple-resource theory, which refers to four dimensions (modalities, stages of processing, codes of processing, and response channels) postulates that predicted interference is more probable if time-shared tasks use resources from dimensions with spatially closer distances.

To understand the seemingly restricted information-processing capacity needed for motor and perceptual or cognitive tasks, in the dual-task literature single and dual-task conditions are used. For example, a primary motor task such as walking or balancing is analyzed when it is either performed as a single task (ST) or when a concurrent secondary task such as serial subtraction, letter-saying, or a reaction time go/no-go task (Beauchet et al., 2005; Beurskens et al., 2014, 2015, 2016a) is added (dual-task condition, DT). In case these two tasks compete for attentional resources within the same domain related to the modality, the stages (perception, cognition, response) or the codes, a more resource-consuming primary or secondary task should then interfere with the respective other task. Based on the specific context or personal factors such as specificity of the chosen tasks, age, familiarity with the tasks, etc., this interference may show in performance decrements, called dual-task costs. In the motor domain, performance outcome as well as production measures (Magill, 2004) have been used to quantify these changes in motor behavior. Some studies exhibited a reduction in gait velocity in DT in children (Beurskens et al., 2015), adults (Mirelman et al., 2014), and seniors (Doi et al., 2013), higher spatiotemporal gait variability in seniors in DT (Beurskens and Bock, 2012) and adults (Mirelman et al., 2014) or an increased number of missteps in seniors (Schrodt et al., 2004).

Dietrich (2006) proposed that reduced gait speed and increased gait variability in DT is due to brain-metabolism demands: integrating gait-related sensory input and motor output plus an extra perceptual-cognitive task may exceed the brain's resources. Also, other studies (Beurskens et al., 2014; Mirelman et al., 2014) investigated cognitive-motor interference on a neurophysiological level (e.g., fNIRS) and showed increased neural activation in a dual-task paradigm. Beurskens et al. (2016c) postulated an increased cognitive load and that upregulated brain activity compensates for dual-task requirements.

Tucker and Stern's (2011) cognitive-reserve theory suggests that individuals differ in their cognitive capacity that allows for situational compensation via the recruitment of additional brain regions and that cognitive capacity is malleable via training interventions. This might be one explanation why other studies do not show any interference between motor and cognitive tasks (Huxhold et al., 2006; Meester et al., 2014). Leone et al. (2017) also reported inconsistent findings including supra-additive activation of brain areas, but also sub-additive activation, in DT performance, presumably related to situational and differential compensation mechanisms in the participants to execute both tasks concurrently with an adequate resource allocation. These ambiguous findings for *when* interference occurs may stem from the low predictive value of the named models for *specific* DT situations. Nevertheless, when predicting the magnitude of interference between a motor task such as body transport inducing optic flow and a concurrent visually based decision-making task, the focus is on the substantial time-shared and overlapping brain resources of these two tasks. Due to this, it can be expected that also overlearned and highly repeated motor skills in elite athletes (e.g., block steps and block jumping) may still be vulnerable to secondary tasks such as concurrent tactical processing.

In addition, there are only few studies which investigated other, more sport-related movements (e.g., jumping performance). Also, there is no study which investigated cognitive-motor interference in a sport-specific game-like situation. So, Dai et al. (2017) showed in a dual-task paradigm including a counting (cognitive) task and a jumping-performance task that cognitive-motor interference resulted in decrements in landing as well as jumping performance.

The aim of the study was to examine how visual information-processing task affect motor-performance in a game-like sport-specific situation in elite volleyball experts. We hypothesized that motor performance would decrease in a game-like dual-task situation due to limited and overlapping resources for perceptual-cognitive processing and motor control. Depending on the complexity of the task, we expected a higher motor-cognitive interference in a perceptual-cognitive dual-task (video, dual-task high) than in an only perceptual dual-task (picture, dual-task low).

MATERIALS AND METHODS

Participants

Twenty-four competitive (beach) volleyball players on international and national top level participated in this study. They were players from first to third division in Germany or members of the highest national beach tour; they had elite, partly junior, status, or were part of the national volleyball team. All subjects had ball practice at least four times up to eight times a week during the study. The age ranged from 14 to 30 years (M = 19.2 years; SD = 4.2) and three of them were male. The athletes were recruited from a German volleyball talent-development center, a first-league volleyball club and other higher-league volleyball clubs from indoor and beach volleyball.

This study was approved by the local ethics committee and informed consent was obtained from all participants (and their parents/legal guardians) prior to any data collection.

Experimental Setup

All measurements were carried out in a motor behavior lab. The test site consisted of a height-adjustable, standard volleyball-net construction (9 m) placed in the middle of the lab. The standard net height for men (2.43 m) and women (2.24 m) was used for testing. To measure volleyball-specific motor-performance parameters (i.e., jumping height and the length of the first step after the ready-block-position), force plates (Kistler®) and Qualysis Track Manager (Qualisys® version 2.15) motion-capture system were synchronized and used for each measurement. In total, eight force plates (size: 60 × 80 cm; 1200 Hz) located in series in front of the net construction and 12 QTM Oqus cameras (400 Hz) were set around the net construction (see **Figure 1**).

Additionally, a 5 × 4 m projection screen was positioned parallel (80 cm) to the net construction. The screen was illuminated via a back projector (Optoma EH505 projector). The projector was located 4 m behind the screen to present the stimuli over the whole surface on the screen. For the presentation of the stimuli on the screen, the Neurobehavioral System (NBS) Presentation® software was used and synchronized with QTM and Kistler systems. Before each measurement, the Kistler and Qualysis systems were calibrated.

Tasks

In this study, a motor performance single-task (i.e., performing isolated block jumps without a second cognitive or perceptual task) and two dual-tasks (performing block jumps plus a perceptual or perceptual-cognitive task) were administered. The setting, starting, and landing area of the players were identical in each task. The starting position was in front of the net, on the middle of force plate number four and five and the landing area was on force plate three (left side) or six (right side).

The following single task and two dual-tasks were implemented:

Single Task (ST)

Participants performed self-initiated isolated, maximal block jumps to the right and to the left side in front of the net construction. The screen in front of the net construction was gray and no volleyball field was shown. The instruction was to jump as high as possible.

Dual-Task Low (DT-L)

Participants performed self-initiated maximal block jumps to the left and right side while a volleyball-specific image was presented on the 5 × 4 m screen via back projection. The static picture depicted an offensive set play of four opponent players (defense, setter, attackers) from a frontal perspective. A freeze frame at the moment of attacking (i.e., ball-hand contact) was created with a GoPro® Hero. There were two matched pictures with attacker from position II (on the left side from the perspective of the participants) and position IV (on the left side from the perspective of the participants). Participants were positioned in front of the screen and observed the picture from the perspective of an opponent block player. The instruction for the participants was to perform a maximal block jump in front of the attacker at the screen.

Dual-Task High (DT-H)

Participants performed maximal block jumps to the right and left side depending on a dynamic perceptual-cognitive load, which consisted of volleyball-specific videos (60 Hz) being presented on the screen via a back projector. The dynamic stimuli were videotaped from a first-person perspective and consisted of four different videos which were created with a GoPro® Hero. (15 Mbit/s; 120 fps) depicting volleyball scenes of offensive set plays with four or five players (defense, setter, attackers). The structure of the offense set play in the videos was always the same: a serve was played at the reception players, a reception was played to the setter, followed by a set play either to position

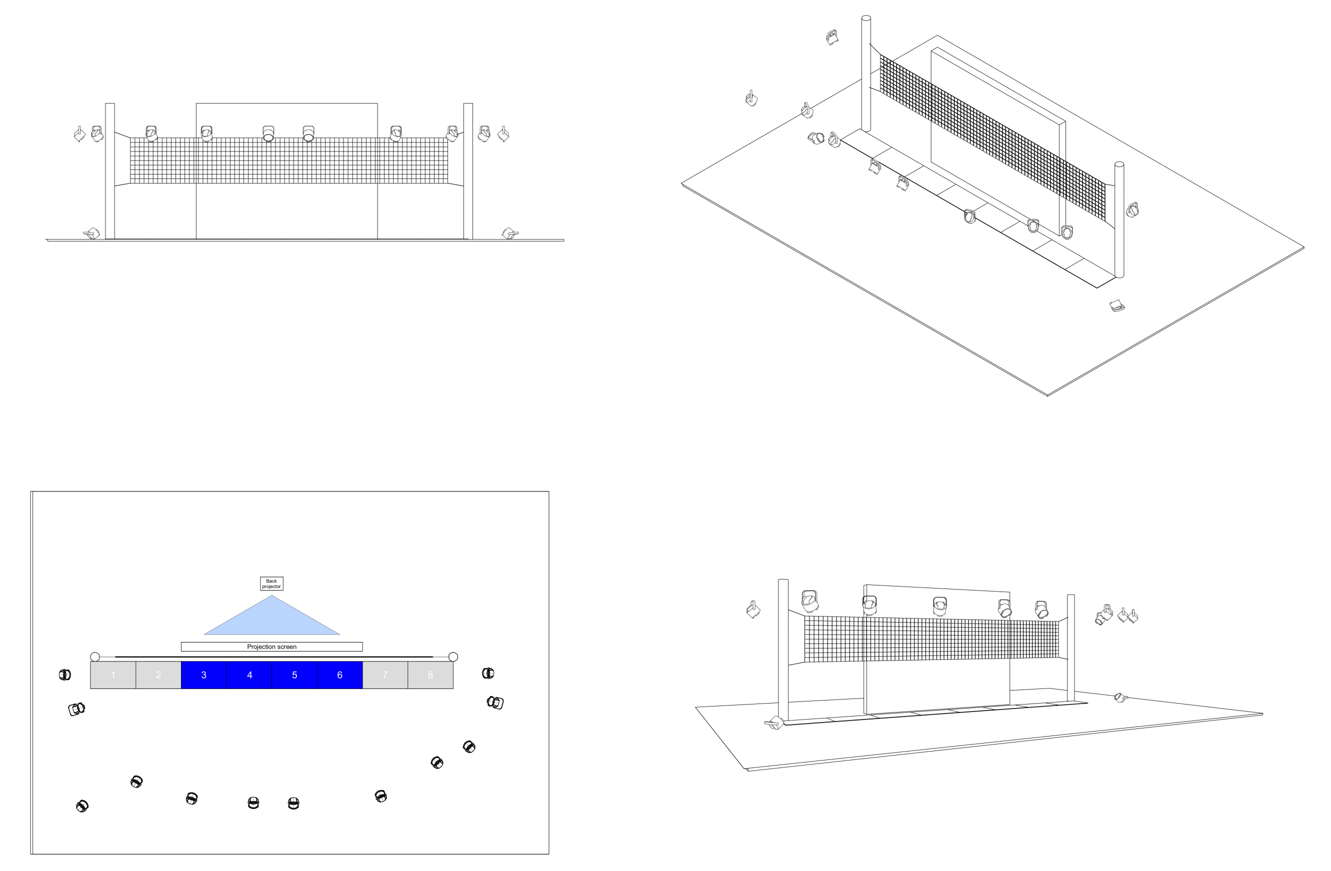

FIGURE 1 | Volleyball setup including net construction, motion capture, force plates, and projection screen.

IV or position II and a respective attack from the opponent or outside hitter. The videos were not occluded and ended after the landing of the hitter. Players in the video were recruited from a first-league club (female). The starting positions of all players in the video were standardized and the attackers were instructed to stand still until the start of their attacking approach.

Participants entered the starting position after a "go"-command by the test conductor. Then, they watched the scene from the perspective of an opponent blocking player with the instruction to observe the scene and to perform a maximal blocking action in front of the attacking player (i.e., on the left or right side).

Procedure

Upon arriving, participants gave informed consent and had an individual and standardized warm-up of 15 min. Then, seven reflective markers were positioned on the back, each big toe, each heel and each hand. To determine the position of the markers in space, a static measurement was conducted. Participants were instructed to stand upright on one of the force plates for 8 s. Upon completing the static measurement, participants started the test session with the three conditions (ST, DT_L, DT_H) in counterbalanced order. In all conditions, participants performed four block jumps with a break of 20 s between each jump and they were reminded before each jump to jump as high as possible.

Data Analysis and Dependent Measures

Each jump trial was processed in the QTM motion capture system (Version 2.15), exported, and calculated by using MATLAB (MathWorks®, Version R2017a). Dependent measure was jumping height. Jumping height was analyzed using the marker at the back of the participants. The vertical distance between the back marker in standing (static measurement) and in the highest point of each jump was calculated with MATLAB (MathWorks®, Version R2017a).

As a supplementary measure of motor behavior, we analyzed the length of the first step after ready-block position. The length of the first step was calculated by using the big-toe marker of the foot that made the first step to the right or left side. The distance between the starting position directly before initiating the jump and the first touch on ground was calculated with MATLAB (MathWorks®, Version R2017a). All participants used the same volleyball-specific blocking technique (i.e., swing block, which is the preferred technique in elite volleyball), consisting of a three-step approach.

Further parameters were volleyball-specific errors (e.g., net touching) and decision accuracy in all trials and conditions. They

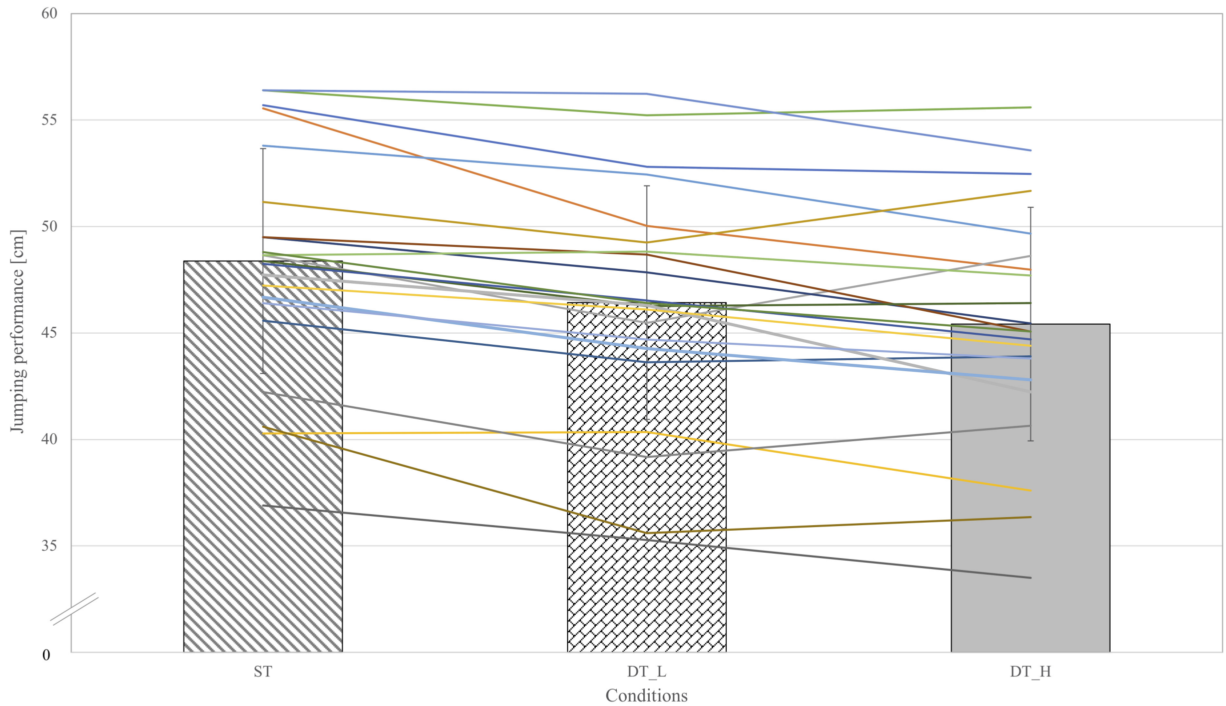

FIGURE 2 | Mean jumping heights over all athletes are presented in the bar graphs (single-task, dual-task low, dual-task high). Individual data of all athletes are in presented in lines.

were recorded by the experimenter via protocol. An invalid trial in decision accuracy was defined when participants performed a step in the wrong direction.

Statistical Analyses

Data of each condition and participant were averaged for analysis with Microsoft Excel Version 16.10 and were analyzed with IBM SPSS statistics 25. Repeated-measures ANOVAs with the within-participant factors ST, DT_L, and DT_H were computed to assess differences in the dependent variables jumping performance and the length of the first step after the ready-block-position. Partial eta square was used as a measure of effect size and the level of significance was at $p < 0.05$. Pairwise comparison with Bonferroni correction were used for all *post hoc* tests. Invalid trials were not analyzed.

RESULTS

Two participants were excluded from all analyses because of too many technique changes between the three conditions.

Jumping Height

Mean jumping performance of all included athletes (see **Figure 2**, bar graphs) and individual data of the participants (see **Figure 2**, lines) was calculated based on the individual means of all participants in each condition. Mean jumping height was 48.4 cm (*SD* = 5.3) in ST. In DT_L, mean jumping height was 46.4 cm (*SD* = 5.5) and 45.4 cm (*SD* = 5.5) in DT_H. The results of a repeated-measures ANOVA show a significant effect of conditions on jumping performance $F(2,42) = 33.64$, $p < 0.001$, $\eta_p^2 = 0.62$. *Post hoc* comparisons reveal that jumping performances in DT_H ($p < 0.001$) and DT_L ($p < 0.001$) were significantly lower than in ST. Between DT_L and DT_H, there was no significant difference ($p = 0.06$).

Length of the First Step After the Ready-Block-Position

The length of the first step after the ready-block-position in the block jumping approach was calculated based on the individual means of all included participants in each condition. **Figure 3** shows the means of the length of the first step after the ready-block-position over all participants in bar graphs. The mean step length in ST was 32.4 cm (*SD* = 22.4), in DT_L 25.9 cm (*SD* = 21.0) and in DT_H 20.2 cm (*SD* = 18.0). The individual data of all athletes are presented as lines in **Figure 3**. The results of the repeated-measures ANOVA shows a significant effect of conditions on the length of the first step after the ready-block-position, $F(2,42) = 7.90$, $p = 0.001$, $\eta_p^2 = 0.27$. *Post hoc* comparisons reveal that step length in ST was significantly longer than in DT_L ($p = 0.028$) and DT_H ($p = 0.005$). Between DT_H and DT_L, there was no significant difference ($p = 0.33$).

Further Parameters

The error rate of included athletes in decision accuracy (i.e., the incongruence between ball direction and direction of motor response) was 5.3% in DT_H. The volleyball-specific errors

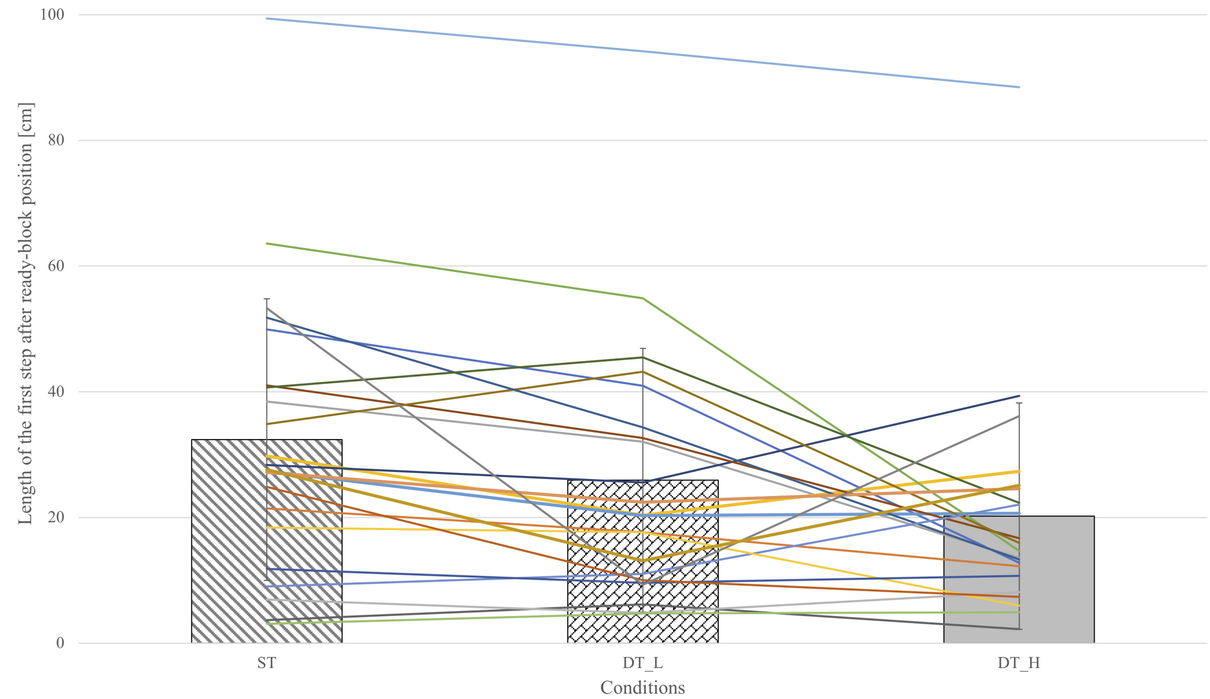

FIGURE 3 | Mean length of the first step after the ready-block-position over all athletes are presented in the bar graphs (single-task, dual-task low, dual-task high). Individual data of all athletes are presented in lines.

(e.g., net touching) amounted to 1.8% in ST; 5.3% in DT_L and 6.2% in DT_H.

DISCUSSION

The aim of the present study was to investigate the performance effects of adding perceptual-cognitive tasks to block jumps with a step approach in a dual-task design. Based on the assumption of time and resource sharing between motor and visual-cognitive processing, we expected a visual (DT_L, dual-task low) and a visual-cognitive (DT_H, dual-task high) task to perturb jump-approaching step length as well as jumping performance compared to single-task block jumping (ST). In accordance to our hypothesis, results show that motor-performance (i.e., jumping height) and motor-execution (i.e., length of the first step after the ready-block-position) parameters decreased when secondary visual-cognitive tasks are added. Jumping heights in the perceptual dual-task condition (static picture, DT_L) and also in the perceptual-cognitive dual-task condition (video, DT_H) were significantly lower compared to ST. Contrary to our expectation, it seems that the complexity of the second task had no effect. The prediction that adding visually based decision-making to block jumping would even further detriment performance can, however, not be corroborated.

For an analysis of the approach steps to block jumping, the length of first step after ready-block position was analyzed as a supplementary measure of motor behavior. The first step after ready-block position was significantly lower in DT_H and DT_L than in ST. Again, differential effects between DT_H and DT_L cannot be revealed.

These findings are in line with previous studies that found dual-task costs in motor measures when combined with perceptual-cognitive tasks (Beauchet et al., 2005; Ruffieux et al., 2015). Many studies used an overlearned primary motor task such as walking that is presumed to be executed with little cognitive effort (e.g., the studies by Beurskens et al., 2016b,c). Cognitive-motor interference would show in, e.g., reduced gait velocity or shorter stride length. Beurskens et al. (2016c) demonstrated that a perceptual-cognitive task such as "serial subtraction" reduced walking performance. Also, Plummer-D'Amato et al. (2011) found reduced walking speed while executing a spontaneous speech test in younger and older adults. They hypothesized that walking as the motor task also requires visual processing (e.g., optic flow, visual cues for balance control, etc.), increasing the likelihood of interference between the tasks. The role of visual processing in conceptual ideas for multiple resources and for prediction of interference has already been highlighted by Wickens (2002). Based on this theory, the decrements of motor performance might be explained by an overlap between visual-processing demands for the dual-tasks.

On the basis of a motor-skills taxonomy (Gentile, 1987), walking or approaching are characterized by body transport. In the proposed dimension "action function," the function of the action is to move the body to a specific location in an allocentric frame. In addition, the environmental context of the task DT_H used here is characterized by in-motion with inter-trial variability, i.e., the conditions are different from one trial to another, as, e.g., the ball's path and speed changes for each trial. Based on our data in DT_H and DT_L, the effect of additional cost via dynamic environments and online decision-making seems small (i.e., no differences between DT_H and DT_L), but the costs of adding visual-processing requirements induces a strong impact on motor behavior (i.e., DT_L and DT_H differ significantly from ST in jumping height and in length of the first step after the ready-block-position).

In this study, we could not find differential effects between the two secondary tasks (i.e., DT_L and DT_H). Bock (2008) showed higher interference of visually demanding tasks compared to memorization or recall tasks for walking. Similarly, Beurskens and Bock (2013) showed higher interference between visually based tasks compared to a verbal-fluency task (i.e., spelling alphabet) and postulated that two tasks with the need for visual processing overstrain shared resources. The conclusion is, therefore, that increasing the load of visual processing induces interference in a body-transport task, but that the costs of adding on-trial visually based decision-making concerning the direction of the blocking action are not evident or negligible in a sample of elite athletes that are highly familiar with both tasks. Furthermore, some practice conditions might have a greater potential to reduce cognitive-motor interference (e. g., dual-task costs) than others (Strobach et al., 2013). Another option that needs more investigation but could not be tested in this study, is the hypothesis that the unaffected athletes would exhibit higher levels of sport expertise in relation to some expert indicators (e.g., years of experiences at international level, sustained success in major international, globally recognized competition, see Swann et al., 2015 or classifying experts' performance on based on a special taxonomy, see Baker et al., 2015). A *post hoc* glance on the individual data of athletes, ranging in age from 14 to 30, suggests that the jumping height in some national team athletes decreased less (e.g., no or only little differences in DT_L or/and in DT_H, see **Figures 2**, **3**). Whether this holds in an adequate sample, may need further and specific exploration in the future.

CONCLUSION

As seen in the review of Zentgraf et al. (2017), this is one of the first studies which investigated interference effects in game-like situations in elite-sport athletes from the national top in their age range. Our results reveal significant decrements in jumping height and in the length of the first step after ready-block position in a sport-specific dual-task situation. This indicated cognitive-motor interference in a highly automated volleyball-specific task in elite athletes. In elite sports, it is essential to tap the full physical potential also in a game situation. However, even overlearned and highly repeated motor performance in elite athletes (i.e., jumping height and length of the first step after the ready-block-position) decreased under secondary visually based tasks. In this vein, it is necessary to analyze sport-specific attentional demands and to investigate whether and how perceptual-cognitive skills might be practiced in a sport-specific way (Zentgraf et al., 2017) to minimize cognitive-motor interference and improve transfer to performance in competition. This will be the focus of upcoming studies.

AUTHOR CONTRIBUTIONS

M-TF prepared the setup together with KZ, collected the data from the participants, analyzed the data, and wrote the manuscript. KZ was grant applicant, developed the research design, supported setup preparation, checked the data, and wrote the manuscript together with M-TF.

FUNDING

This project was supported by the Bundesinstitut für Sportwissenschaft (Federal Institute of Sports Science) in 2016 and 2017; grant number 070703/16-17, title: "Training der Geteilten Aufmerksamkeit im Volleyball: Durch Perzeptuell-Kognitive Expertise zum Erfolg."

ACKNOWLEDGMENTS

We thank Yannick Brodatzki and Svenja Wirtz for support in data collection and Marc de Lussanet for support in data analysis. We would also like to cordially thank all the coaches from the National Volleyball Centre and the National League Club in Münster, Germany (Christian Wolf, Ralph Bergmann, Andreas Vollmer) and all the athletes for their time and engagement in this study.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 06 July 2018
doi: 10.3389/fpsyg.2018.01075

Contribution of the Lateral Prefrontal Cortex to Cognitive-Postural Multitasking

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OPEN ACCESS

Edited by:
Eliot Hazeltine, University of Iowa, United States

Reviewed by:
Alexander Soutschek, Universität Zürich, Switzerland
Luis Augusto Teixeira, Universidade de São Paulo, Brazil

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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *02 February 2018*
Accepted: *07 June 2018*
Published: *06 July 2018*

Citation:
Stelzel C, Bohle H, Schauenburg G, Walter H, Granacher U, Rapp MA and Heinzel S (2018) Contribution of the Lateral Prefrontal Cortex to Cognitive-Postural Multitasking. Front. Psychol. 9:1075. doi: 10.3389/fpsyg.2018.01075

There is evidence for cortical contribution to the regulation of human postural control. Interference from concurrently performed cognitive tasks supports this notion, and the lateral prefrontal cortex (lPFC) has been suggested to play a prominent role in the processing of purely cognitive as well as cognitive-postural dual tasks. The degree of cognitive-motor interference varies greatly between individuals, but it is unresolved whether individual differences in the recruitment of specific lPFC regions during cognitive dual tasking are associated with individual differences in cognitive-motor interference. Here, we investigated inter-individual variability in a cognitive-postural multitasking situation in healthy young adults (n = 29) in order to relate these to inter-individual variability in lPFC recruitment during cognitive multitasking. For this purpose, a one-back working memory task was performed either as single task or as dual task in order to vary cognitive load. Participants performed these cognitive single and dual tasks either during upright stance on a balance pad that was placed on top of a force plate or during fMRI measurement with little to no postural demands. We hypothesized dual one-back task performance to be associated with lPFC recruitment when compared to single one-back task performance. In addition, we expected individual variability in lPFC recruitment to be associated with postural performance costs during concurrent dual one-back performance. As expected, behavioral performance costs in postural sway during dual-one back performance largely varied between individuals and so did lPFC recruitment during dual one-back performance. Most importantly, individuals who recruited the right mid-lPFC to a larger degree during dual one-back performance also showed greater postural sway as measured by larger performance costs in total center of pressure displacements. This effect was selective to the high-load dual one-back task and suggests a crucial role of the right lPFC in allocating resources during cognitive-motor interference. Our study provides further insight into the mechanisms underlying cognitive-motor multitasking and its impairments.

Keywords: balance, dual task, fMRI, postural control, working memory

INTRODUCTION

Multitasking comprises a temporal overlap in the performance of different tasks (Wickens, 1980; Pashler, 1994) and performance costs in multitasking are often assumed to depend on the recruitment of common resources in both tasks (Kahneman, 1973; Tombu and Jolicoeur, 2003). While concurrent performance of two cognitive tasks has been associated with additional processing demands in the lateral prefrontal cortex (lPFC; D'Esposito et al., 1995; Schubert and Szameitat, 2003), little is known about the role of the lPFC in the concurrent processing of cognitive tasks and complex motor tasks such as keeping balance on an unstable surface.

Human postural control affords the control of the body's position in space for the purpose of stability and orientation (Shumway-Cook and Woollacott, 2017). Adequate postural alignment is not just a passive state but requires targeted muscle activation through the interplay of the peripheral and central nervous system, including information processing in the proprioceptive, cutaneous, visual, and vestibular systems (Peterka, 2002; Baudry, 2016). Evidence from several methodological approaches indicates an involvement of higher (central) level processes in postural control (Jahn et al., 2004; Jacobs and Horak, 2007; Taube et al., 2008; Lau et al., 2014; Papegaaij et al., 2014; Varghese et al., 2015; Wittenberg et al., 2017). Besides sensory and motor systems, there is evidence that the lPFC is involved in human postural control as well. For example, functional imaging revealed an activation of the lPFC in imagined stance (Jahn et al., 2004). Moreover, balance training in young adults resulted in increases in prefrontal gray matter volume and prefrontal fiber connections (Taubert et al., 2010). Also, using functional near-infrared spectroscopy (fNIRS), Mihara et al. (2008, 2012) provided direct evidence for prefrontal contributions to human postural control. This prefrontal contribution may in turn be responsible for interference with cognitive control tasks known to recruit regions of the lPFC as well (Duncan and Owen, 2000; Fuster, 2001).

A number of behavioral studies showed interference effects during the concurrent performance of motor tasks involving postural control or gait and cognitive control tasks, with particularly pronounced effects in old adults (Woollacott and Shumway-Cook, 2002; Rapp et al., 2006; Granacher et al., 2011; Boisgontier et al., 2013). Evidence for an association of lPFC activation and these interference effects is limited and mostly restricted to regionally unspecific methodological approaches (Holtzer et al., 2011; Doi et al., 2013; Zhou et al., 2014; Little and Woollacott, 2015). For example, an fNIRS study revealed that dual-task "walking while talking" is associated with higher prefrontal activation than single-task walking in both young and old adults (Holtzer et al., 2011). In this study, the dual-task condition included to walk at self-selected gait speed while concurrently naming every second letter of the alphabet. During dual-task compared to single-task walking, higher oxygenation levels in the lPFC were present in young and old individuals. Another fNIRS study tested the role of individual differences in working memory capacity during the concurrent performance of a postural task and a Stroop task (Fujita et al., 2016). Findings from this study showed dual-task-related lPFC recruitment to be associated with working memory capacity with greater dual-task effects in high span participants. Furthermore, transcranial direct current stimulation (TDCS) over the lPFC improved balance and gait performance in cognitive-motor dual-task situations involving a serial subtraction task in young adults (Zhou et al., 2014).

While these studies show a general involvement of the lPFC in cognitive-motor dual tasks, little is known about the specific lPFC sub-regions that are involved in the processing of cognitive-motor dual tasks. This could be investigated by using spatially more precise neuroscientific methods such as functional magnetic resonance imaging (fMRI) and by applying a task design that allows investigating specific cognitive demands related to multitasking. Clearly, a methodological limitation of using fMRI in balance research is that it is not possible to measure brain activity and whole body balance performance within the same session [but see Al-Yahya et al. (2016), Papegaaij et al. (2017) for recent approaches using balance and gait simulation tasks]. However, by correlating individual variability in dual-task-specific brain activity (i.e., cognitive dual-task compared to single-task activity) with individual variability in performance costs in a cognitive-postural triple vs. dual task, the cognitive and neural underpinnings of cognitive-postural interference can be deduced.

In a cross-sectional study, as part of a larger-scale multimodal study, we tested potential associations between an lPFC demanding dual one-back working memory task using fMRI and performance costs in a cognitive-postural task measured on a force plate in healthy young adults. Of note, fMRI and force plate testing was realized in different test sessions. Several studies showed the degree of right lPFC recruitment to be associated with individual differences in various cognitive control tasks (Locke and Braver, 2008; Jimura et al., 2010; Heinzel et al., 2016). In these studies, either intra- or inter-individual increases in right lPFC activity were related to better task performance. This has been associated with increased neural effort in cognitive tasks by which individuals improved performance despite increases in cognitive demands or lower working memory capacity (Eysenck et al., 2007; Barulli and Stern, 2013). Accordingly, we expected dual-task-specific activity in the right lPFC to be associated with cognitive-postural performance costs. More specifically, we expected increased right lPFC activity in dual compared to single one-back tasks to be associated with relative performance costs in a postural task that is performed concurrently with a dual-one back task, that is when cognitive task load is high.

MATERIALS AND METHODS

Participants

Thirty-one young adults participated in this study after verbal instructions were provided and written informed consent was given. Participants were mainly recruited through student mailing lists at the University of Potsdam, Germany, in the context of a large-scale study also involving electroencephalographic (EEG) measurement. Two participants had to be excluded from the analysis – one due to technical failure of the force plate and one due to strong movement during MRI measurement. Thus, the final sample consisted of 14 male and 15 female participants with a mean age of 24.8 years (range: 19–30 years).

All participants were healthy with no adverse signs or self-report of neurological or psychiatric disorders, no hearing impairments, normal or corrected-to-normal vision. Furthermore, suitability for MRI measurement was assessed through self-report.

Participants came to the biomechanics laboratory of the Division of Training and Movement Sciences, University of Potsdam for two test occasions and thereafter to the Berlin Center for Advanced Neuroimaging, Charité Berlin for MRI measurement. Test sessions were separated by a minimum of 1 week and a maximum of 4 weeks. Before the first test session, participants were screened for eligibility via telephone interviews and received a set of questionnaires via mail.

This study was designed according to the latest version of the Declaration of Helsinki and was approved by the local ethics committees of the University of Potsdam and the Charité Universitaetsmedizin Berlin, Germany. Study participation was reimbursed monetarily with 60 € for three test sessions.

Experimental Tasks

While standing on the force plate and during MRI measurement, participants performed single one-back tasks and dual one-back tasks, which covered a range of input stimuli and output responses (see **Figure 1**). For each delivered stimulus, participants had to decide whether it was the same as the previous one (one-back). Throughout testing, participants wore headphones with an attached microphone. During the balancing task on the force plate, all participants were equipped with a response key in their right hand, which allowed them to press a button with their right thumb. Inside the scanner, participants used their right index finger. The following cognitive and postural tasks were applied:

Single One-Back Tasks

Participants performed different versions of a spatial one-back working memory task. An instruction trial before each block indicated them the task for the following block. Input stimuli were either visual or auditory and responses were given either manually or vocally. The stimulus duration was 500 ms followed by a fixation inter-stimulus interval of 1500 ms. Task blocks consisted of 16 trials, including 5 one-back targets and 11 non-targets in pseudo-random order. By combining the different input stimuli and output responses, there were four different types of cognitive single one-back tasks.

Visual-manual one-back task

The target display consisted of a black background with a white fixation cross in the center. Visual stimuli were presented as white squares located at six different spots on the screen (up, center, down), three on each side of the fixation cross. Participants were instructed to respond fast and correctly by pressing a button whenever the position of the current square was the same as in the preceding trial.

Auditory-vocal one-back task

Three different tones were presented at frequencies of 200, 450, 900 Hz via headphones while a static fixation cross was displayed on the screen. The tones were presented either to the left or the right ear, resulting in six different stimuli. As in the visual task, participants were instructed to respond fast and correctly, when the same tone was presented to the same ear in trials n and n-1. Participants were instructed to respond vocally to target stimuli by saying "yes" (German: "Ja").

Visual-vocal one-back task

The target display and stimulus presentation were the same as in the visual-manual one-back task. However, in this case participants had to respond vocally to target stimuli by saying "yes" (German: "Ja").

Auditory-manual one-back task

Targets and stimulus presentation were the same as in the auditory-vocal condition. However, during this experimental condition participants had to respond manually to target stimuli via button press.

Dual One-Back Tasks

In dual-task blocks, participants performed two one-back tasks simultaneously. For this purpose, a visual and an auditory stimulus were presented simultaneously for 500 ms, followed by a 1500 ms inter-stimulus interval. Participants were instructed to decide for both presented stimulus modalities whether the stimulus was identical or not to the prior stimulus (dual one-back task). In dual one-back task blocks, both the visual-manual and the auditory-vocal task were performed simultaneously or the visual-vocal and the auditory-manual task were performed simultaneously. Accordingly, there was no overlap in stimulus modality or response modality in either dual one-back task. For each task block, five one-back targets were presented, i.e., two or three in the visual modality and two or three in the auditory modality. One-back targets were presented either in the auditory or in the visual modality but never simultaneously.

Postural Baseline Task on Force Plate

With their arms hanging loose to the sides of the body, participants were instructed to stand as still as possible in semi-tandem stance on an unstable surface (i.e., balance pad) with the dominant leg posterior to the non-dominant leg. To determine participants' dominant leg, we asked them to softly kick a ball placed approximately 1.5 m right in front of the participant. We registered the kicking leg as the dominant leg. Further, participants answered two questions of the lateral preference inventory (Coren, 1993) concerning leg dominance: (i) which leg would you use to pick something up from the ground? and (ii) which leg would you use to step on a burning cigarette on the ground? We defined the dominant leg as the leg, which was the one that was most often mentioned/used in these three situations. The balance pad was placed on a one-dimensional force plate (Leonardo 105 Mechanograph®; Novotec Medical

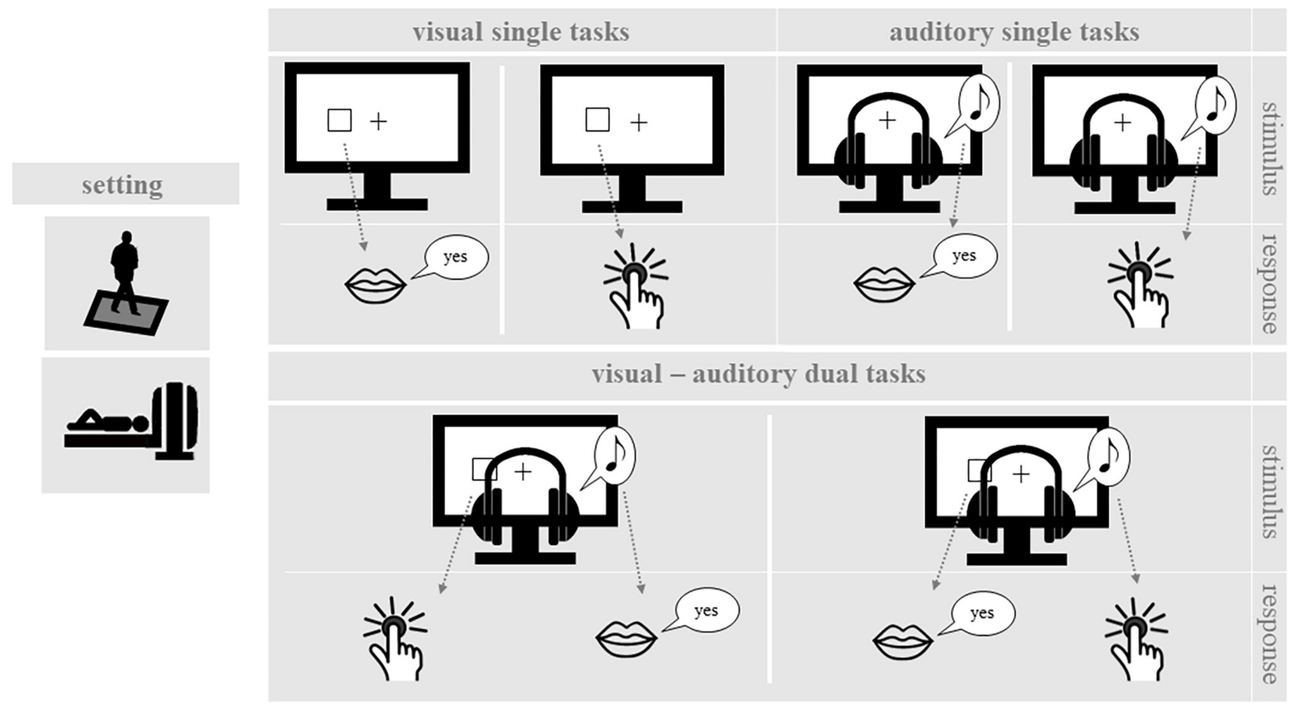

FIGURE 1 | One-back working memory tasks. In the single one-back tasks, participants decided for visual or auditory stimuli whether they are identical to the stimulus in the trial before. In the dual one-back tasks visual and auditory stimuli were presented simultaneously and participants made the one-back decision for both stimuli.

GmbH Pforzheim, Germany) in order to measure total CoP displacements during testing. Participants had to keep their head straight and their gaze fixated either on a stable visual stimulus (*stable fixation condition*) or on a dynamic visual stimulus (*dynamic fixation condition*). In the stable fixation condition, participants had to focus their gaze on a fixation cross which was presented in the center of the screen. In the dynamic fixation condition, a fixation cross and an ampersand symbol ("&," fontsize: 54) were displayed alternately in the center of the screen, with presentation times matched to presentation times in the cognitive tasks (i.e., 500 ms ampersand, 1500 ms fixation). Here, we only report the dynamic fixation condition, as our pilot studies revealed higher postural instability during stable fixation.

Procedure

The first test day comprised a neuropsychological screening procedure, including tests for vision and hearing abilities and several specific neuropsychological and motor tests (e.g., Digit Span, Trail Making A & B, Timed Up & Go Test). These neuropsychological tests were included to compare the young adults as a control group to a cohort of old adults who underwent further experimental sessions as well as a cognitive-motor training procedure (to be reported elsewhere). At the end of the session, participants practiced the single and dual one-back tasks, with two blocks including 32 trials for each single one-back task and four blocks of 32 trials for each dual one-back task after detailed instructions.

On the second test day, participants performed the experimental tasks as outlined above which included the assessment of total CoP displacements while standing on the force plate and the concurrent recording of EEG data using a mobile 64-channel EEG system (EEG data not reported here). The experiment consisted of two sessions with six runs each. Within each run, three one-back task blocks were performed (two single one-back tasks, one dual one-back task). In each session, three runs were conducted in standing upright position and three while sitting upright, performed in an alternating mode. The sessions differed in the specific stimulus-response mappings to be performed, i.e., in one session only visual-manual and auditory-vocal tasks were realized, in the other session only visual-vocal and auditory manual tasks (see Stelzel et al. (2017) for more details).

All participants performed both sessions in direct succession with a short break in-between and the order of the sessions was counterbalanced between participants. All participants started in the semi-tandem stance condition. The standing condition always began with one stable fixation block, followed by a dynamic fixation block (33 s each to match the duration of the cognitive tasks). Thereafter, the three cognitive task blocks followed (two single one-back blocks and one dual one-back block, the order counterbalanced across runs, 33 s each) which were again followed by one dynamic fixation block and one static fixation block. Each cognitive task block included 16 trials. While sitting, only the three cognitive task blocks were performed in the same order as in the preceding standing condition.

Participants practiced the relevant tasks one more time at the beginning of the second test day right before the experimental session in sitting position (one task block per single one-back task, two task blocks per dual one-back task) started.

The third test day included the MRI measurement. Here, the same single and dual one-back tasks were performed in a block design. There were six runs for this experiment with six task blocks per run. As in the previous session, visual-manual, and auditory-vocal tasks were performed in three runs and visual-vocal and auditory manual tasks in the other three runs. The different types of runs were alternated. Each run consisted of four single-task blocks and two dual-task blocks. Single- and dual-one-back task blocks were again counterbalanced in their order across runs. The order of runs was counterbalanced across participants. Block duration was 34 s, inter block intervals were 12 s (gray fixation cross), followed by 2 s of instructions for the next task block.

During the MRI session, participants performed three additional tasks: the MRI session always started with a zero-back task. After the one-back task, which is subject of the current paper, a resting state measurement and a task switching experiment were conducted. These data will be reported elsewhere.

Performance Assessment and Analysis

Cognitive Performance

Visual and auditory stimuli were presented, and manual and vocal responses were recorded via Presentation software[1]. Performance data of the cognitive tasks were calculated as p(Hit)-p(False alarm). Vocal and manual responses were recorded during the experiment for the period of each one-back trial duration (2 s). Vocal data were analyzed offline with a self-developed Matlab tool (MathWorks; Natick, MA, United States). The custom-made tool (Reisner and Hinrichs, 2016) was developed to facilitate automated identification of trials with correct vocal responses and to extract reaction time (RT) latencies based on simple signal amplitude measurement. The tool was validated successfully via manual coding of vocal responses (Cohens Kappa = 0.941, $p < 0.001$). Due to technical failure during recording, the vocal data of eight young participants were not recorded properly in the force plate session and could not be analyzed. These participants were excluded from all analyses including one-back performance data from the force plate session but were included in the analysis of fMRI and CoP data. Cognitive performance data were averaged for all single tasks and dual tasks, respectively.

These data were then subjected to a general linear model (GLM), with two within subject factors with two levels each: 1. Force plate vs. MRI × 2 single one-back vs. dual one-back task. In addition to these performance measures, mean RTs for correct target responses are reported.

Additionally, relative performance costs in p(hit)-p(false alarm) in the dual one-back task were calculated in relation to the single one-back task [(Single-Dual)/Single)*100] to then calculate the correlation of cognitive performance costs with postural performance costs.

Balance Performance

Postural sway was assessed during semi-tandem stance (barefoot or with socks) on an unstable surface (i.e., balance pad) with the dominant leg posterior to the non-dominant leg. The balance pad (Airex®) was placed on a one dimensional force plate. Total CoP displacements (mm) were computed using CoP displacements in medio-lateral and anterior-posterior directions by means of the Pythagorean theorem. Assessment duration (34 s) was chosen in order to optimize reliability of postural sway measurement (Le Clair and Riach, 1996) and in accordance with the cognitive task requirements.

For statistical analysis, we ran an exploratory data analysis using JMP® software (JMP® 8, SAS Institute GmbH, Germany) to exclude outlier blocks for each participant. Outlier blocks were identified by box plot analyses on the subject level and defined as blocks which were outside the whiskers, that is blocks that were outside the range of <1st quartile – 1.5*interquartile-range or >3rd quartile + 1.5*interquartile range. Altogether, 2.8% outlier blocks were identified and excluded from further analyses.

Performance data of total CoP displacements for the baseline postural task (P), plus cognitive single one back task (CP), plus cognitive dual one-back task (CCP) were calculated by averaging CoP displacements of the respective conditions. Relative multiple task costs for total CoP-displacements were calculated for each run and averaged per condition according to the formula of Doumas et al. (2008). Thus, relative dual-task costs of total CoP displacements during single one-back performance were calculated as ([CP-P]/P) * 100, and during dual one-back performance as ([CCP-P]/P) * 100. To examine assumed effects of task load, we used paired t-tests (CP vs. CCP). All statistical analyses were processed using IBM SPSS Statistics, Version 22.0. Effect sizes (partial eta squared [η_p^2], Cohen's *d*) are reported for all analyses to characterize the effectiveness of the experimental factors.

fMRI Acquisition

All images were acquired using a 3 Tesla Siemens TIM Trio MRI scanner with blood oxygen level-dependent (BOLD) contrast and a 12-channel head coil at the Berlin Centre for Advanced Neuroimaging (BCAN, Berlin, Germany). Head motion was limited using foam head padding for comfortable stabilization. Participants were provided with earplugs and headphones to dampen scanner noise and enable communication. Experimental stimuli were presented with Presentation software (Neurobehavioral Systems, see footnote 1) and projected onto a screen positioned at the head end of the bore, viewable through a mirror attached to the head coil. Behavioral performance was also recorded with Presentation software via a fiber optic response keypad and an MRI-compatible microphone (FOMRI III^{TM}+ microphone by Optoacoustics).

T2-weighted echo-planar images (EPI) were performed in six runs (echo time TE = 30 ms, flip angle = 78°, field

[1] https://www.neurobs.com/

of view = 24 cm, matrix size = 64 × 64, TR = 2 s, slice thickness = 3 mm, inter-slice gap = 0.75 mm). Each run contained 150 volumes with 33 axial slices each. All slices were oriented to the anterior–posterior commissure plane based on an auto-align procedure. Furthermore, field maps were acquired between the third and the fourth run of the experiment using the same slice prescriptions as for functional scans. After the experiment, a structural T1-weighted 3-D MPRAGE scan was performed (matrix size 256 × 256 × 192, slice thickness: 1.0 mm). Anatomical images were used for the normalization of the functional data to the Montreal Neurological Institute (MNI) atlas space.

fMRI Data Analyses

All analyses of functional MRI data were performed with Statistical Parametric Mapping software (SPM12[2]). The functional volumes of each participant were first realigned and unwarped, then co-registered to the anatomical image. Participants with high movement (>1 mm within run, rotations > 1°) were excluded from further analyses. This was the case for only one participant. Subsequent preprocessing stages included segmentation of the anatomical images and spatial normalization of the functional datasets into standard MNI space by applying the parameters of the normalization of the anatomical image. Finally, functional data were smoothed with an 8 mm FWHM Gaussian kernel and high-pass filtered to a cut-off of 1/124 Hz during statistical analyses. An analytic design matrix was constructed modeling onsets and duration of each task condition for each participant and a GLM for serially auto-correlated data was applied (Friston et al., 1995). The functional volumes acquired during the six runs were treated as separate time series.

The data were analyzed as a block design including one covariate for each type of single one-back task (visual-manual, auditory-vocal, visual-vocal, auditory manual) and one for each dual one-back task (visual-manual and auditory-vocal, visual-vocal, and auditory-manual), represented by boxcar functions with a duration of 34 s. Additional covariates were included for instructions (2 s), fixation periods (12 s) between the blocks and six movement parameters as covariates of no interest. Regression parameters were estimated using the classical restricted maximum likelihood (ReML) algorithm.

On the second level, one-sample t-tests were used to test for dual-task-specific activity, i.e., the contrast of all dual tasks with all single tasks. A cluster-wise family-wise error (FWE) correction was used to correct for multiple comparisons, with a threshold of $p < 0.05$ FWE at the cluster level (and $p < 0.001$ at the voxel level).

To assess whether dual-task-specific regions in the lPFC were associated with performance in the postural task, individual CoP displacements (relative task costs) were entered as covariate in the respective one-sample t-tests for single and dual one-back tasks. The respective correlation was visualized by averaging the beta values of all voxels obtained in this whole brain analysis and plotting these.

[2]http://www.fil.ion.ucl.ac.uk/spm

RESULTS

Behavioral Data

Cognitive Performance

The repeated measures ANOVA on p(hit)-p(false alarm) performance with factors session (force plate vs. MRI) and task load (single vs. dual one-back task) revealed an effect of task load, F (1,20) = 70.0, $p < 0.001$, $\eta_p^2 = 0.78$, with lower performance in the dual one-back tasks [Mean (M) = 0.87, Standard error (SE) = 0.02] compared to the single one-back tasks (M = 0.97, SE = 0.02). In the whole group, the additional postural task did not affect this performance, as indicated by non-significant effects of session and interaction session × task load (see **Figure 2A**, left panel). Thus, while cognitive task load clearly deteriorated working-memory performance, the additional postural task did not in this sample of young participants.

The analysis of RT data also revealed an effect of task load, F (1,20) = 170.1, $p < 0.001$, $\eta_p^2 = 0.90$, with higher RTs in the dual one-back task (M = 877.73, SE = 33.32) compared to the single one-back task (M = 617.67, SE = 23.77; see **Figure 2A** right panel). Additionally, participants responded slower in the MRI session (M = 796.95, SE = 29.95) than in the force plate session [M = 698.45, SE = 25.71, F(1,20) = 59.28, $p < 0.001$, $\eta_p^2 = 0.75$]. Dual-task costs were more pronounced in the force plate session (mean difference single vs. dual task M = 278.10, SE = 21.18) than in the MRI session (M = 242.02, SE = 20.56) as indicated by the significant interaction effect of session × task load, F(1,20) = 8.57, p = 0.008, $\eta_p^2 = 0.30$.

Balance Performance

For the analysis of total CoP displacements (n = 29), relative performance costs were calculated in relation to the single postural task condition (dynamic fixation; see **Figure 2B** for absolute total COP displacement values). This analysis of performance costs revealed a significant difference between the postural condition with additional single one-back task performance (mean costs M = 2.47%, SE = 1.74) and the condition with additional dual one-back task (M = −1.72%, SE = 1.52, t(28) = 2.52, p = 0.018, d = 0.48). CoP values in both conditions did not differ significantly from the baseline condition (p's > 0.16). Note, however, that the relative performance costs in the postural task varied strongly between individuals as indicated by the high standard errors.

Correlation Between Cognitive and Postural Performance Costs

To address the question whether dual-task costs in the cognitive domain (p(hit)−p(fa)) were associated with the triple-task costs in the postural domain, we correlated the cognitive dual-task costs from the MRI session with the COP costs in the force plate session. Both measures were correlated, r = 0.48, p = 0.008 (**Figure 2C**), suggesting that those individuals with high cognitive costs in the comparison of dual vs. single one-back tasks also had higher costs in the postural task when performed concurrently with the dual-one-back task on the force plate.

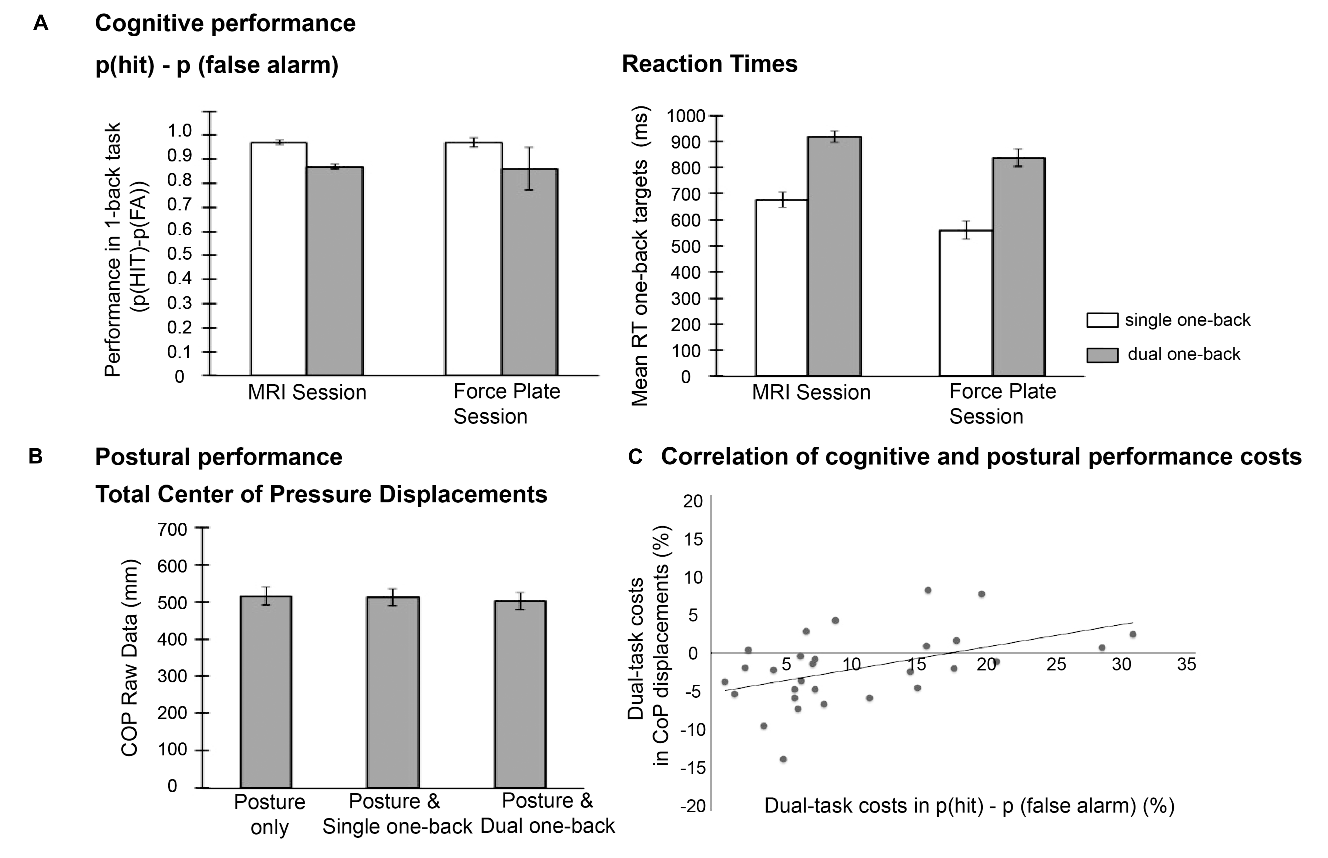

FIGURE 2 | (A) Mean cognitive performance data, **(B)** mean postural performance (raw data), and **(C)** correlation of performance costs in both domains.

Functional Imaging Data

Dual Task-Related Effects

Figure 3 shows the dual-task-specific activity revealed by contrasting all dual-task blocks with all single-task blocks. The activity spans a fronto-parietal network involving bilateral lPFC as well as superior parietal regions. Also occipital and inferior temporal regions were more active in dual one-back working memory blocks than in single one-back blocks (see **Table 1** for all activity peaks).

Brain-Behavior Correlations

To test whether the degree of lPFC involvement in the high load dual one-back working memory task is related to the degree of performance costs in CoP displacements in the postural task, relative costs in total CoP displacements during dual one-back performance minus single one-back performance were entered as a covariate in the analysis. This analysis revealed that individual variability in the activity in a region in the right middle frontal gyrus in the mid-lPFC ($x = 44$, $y = 30$, $z = 32$, $k = 59$ voxels, $p < 0.001$, uncorrected) was positively correlated with the increase in relative costs in total CoP displacements while performing the dual one-back task on the force plate (see **Figure 4**). That is, individuals, who recruited the lPFC to a higher degree in a cognitive dual task, were less able to control their posture in addition as revealed by larger costs in CoP displacements. No such effect was present for the single one-back tasks. A *post hoc* analysis revealed that the right lPFC region overlapped partially with the dual-task-specific network identified in the group analysis ($k = 35$ voxels). In addition, the cluster partly overlapped ($k = 36$) with the *n*-back-associated right DLPFC region defined as a literature-based probabilistic region of interest by Heinzel et al. (2014). A small volume correction with this right DLPFC mask revealed that this sub-cluster was significant with $p < 0.05$ FWE-cluster corrected within this mask.

DISCUSSION

In the present fMRI study, we aimed to specify the contribution of the lPFC to interference processing in cognitive-motor multitasking situations. In a sample of healthy young adults, we showed a high degree of individual variability in (i) cognitive-motor interference between a postural task and a demanding dual one-back task on a behavioral level and in, (ii) lPFC recruitment during performance of the dual-one back task. Most importantly, we showed an association between these two variables – participants with higher interference costs in total CoP displacement were also characterized by higher dual-task-specific recruitment of the right middle frontal gyrus.

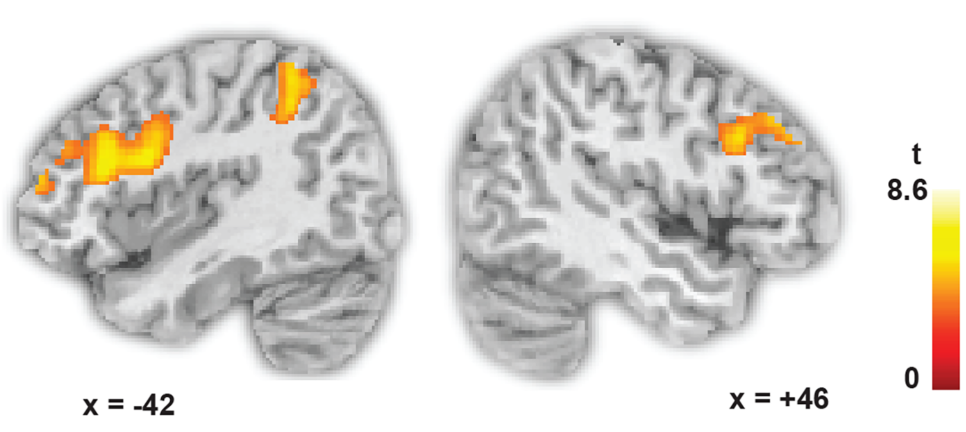

FIGURE 3 | Dual-task-specific brain activity, revealed by contrasting all dual-task blocks with all single-task blocks ($p < 0.05$ FWE cluster-corrected, $p < 0.001$ at the voxel level).

TABLE 1 | Activity peaks for the contrast dual tasks minus single tasks.

Region (labels for $k > 10$)	Hem	Brodmann Area	MNI coordinates			*T*-value	cluster size
			x	*y*	*z*		
Superior parietal lobule, precuneus, inferior parietal lobule, middle occipital gyrus, postcentral gyrus, superior occipital gyrus, supramarginal gyrus, angular gyrus	L	7, 40, 19, 5	−6	−70	58	8.64	3146
			−30	−58	50	8.60	Included
			−34	−48	40	7.10	Included
Inferior temporal gyrus, middle temporal gyrus, middle occipital gyrus	L	37, 19	−52	−56	−8	7.75	389
Middle frontal gyrus, superior frontal gyrus, precentral gyrus	L	6	−30	2	68	7.62	454
Cerebellum	L/R		−4	−82	−26	7.04	846
			6	−84	−32	6.62	Included
Middle frontal gyrus, inferior frontal gyrus, precentral gyrus, superior frontal gyrus	L	9, 46, 10, 6	−40	28	20	6.09	1580
			−40	10	24	5.98	Included
			−38	52	12	5.55	Included
Middle frontal gyrus, inferior frontal gyrus, superior frontal gyrus	R	9, 46, 10	46	20	30	5.30	520
			50	28	34	5.24	Included
			44	40	32	4.86	Included
Superior parietal lobule, angular gyrus, inferior parietal lobule, precuneus, superior occipital gyrus, middle occipital gyrus	R	7, 40, 19	34	−60	50	5.16	416
			34	−66	42	4.85	Included
			22	−74	52	3.61	Included

$p < 0.05$ FWE cluster-corrected, $p < 0.001$ voxel level.

To our knowledge, this is the first study to show that a specific sub-region of the prefrontal cortex, i.e., the middle part of the right MFG is associated with cognitive-postural task interference in healthy young adults (but see Al-Yahya et al. (2016) for corresponding findings in a gait task in a stroke sample). This finding suggests an overlap between the resources required to successfully process interference between two cognitive tasks and between cognitive and postural tasks. It can be postulated that individuals with greater dual-task-specific lPFC recruitment have less neural capacity available to concurrently perform a postural task and vice versa. Note, that this association was not present for the single one-back task, which might be indicative of a load-dependent effect. Thus, even though lPFC activity during the postural task was not measured

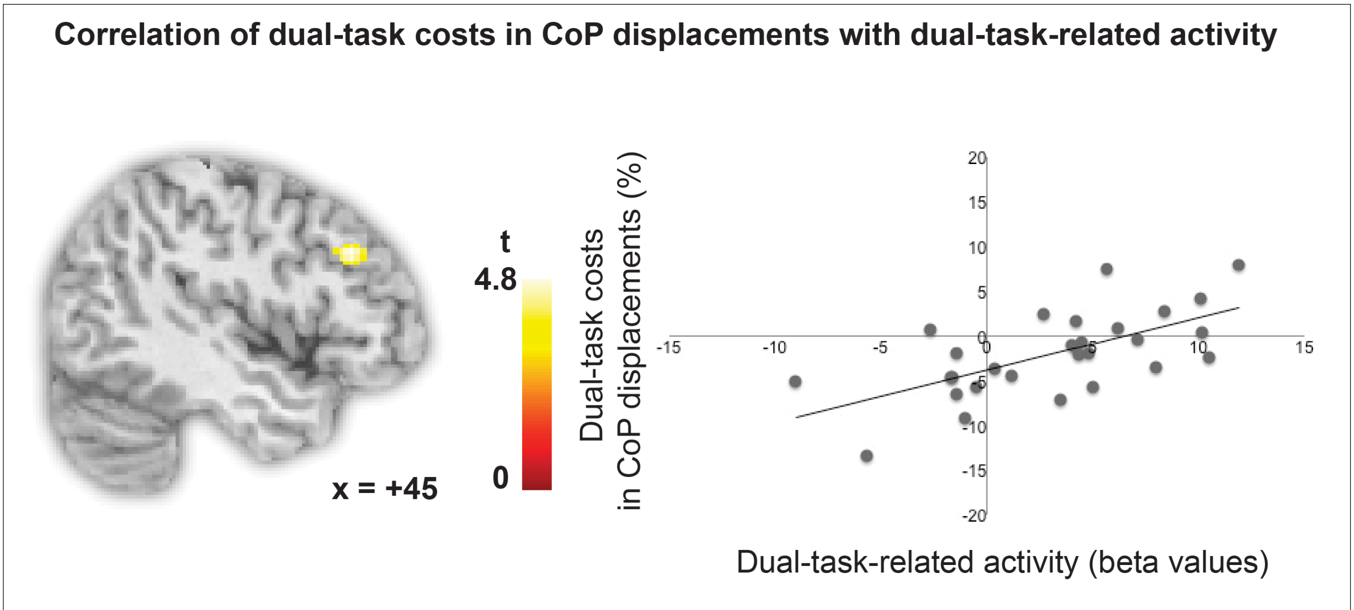

FIGURE 4 | Correlation of relative costs in CoP displacements with dual-task-specific brain activity.

directly, the data from this association approach might support the notion that the lPFC is involved in postural control even in young adults.

Interestingly, lPFC activity was not directly related to cognitive task performance as measured by p(hit)-p(false alarm). This might indicate that some participants modulate their prefrontal activity in order keep an average performance level. This is in line with the neural efficiency hypothesis (Eysenck et al., 2007; Barulli and Stern, 2013), which denotes that less prefrontal neural recruitment during a comparable performance level may constitute a more efficient cognitive control system. This again enables participants to allocate more attention to concurrent tasks, resulting in better performance in this task. Also, during working memory tasks, an increase in fronto-parietal neural activation with increasing cognitive load has been described in terms of an adaptive mechanism in younger adults (Nagel et al., 2011; Heinzel et al., 2014; Heinzel et al., 2017). Accordingly, our findings further contribute to the idea that individuals who vary in their cognitive abilities might compensate for this by investing greater effort. This, in turn, might produce costs in additional tasks requiring overlapping resources, such as the postural task in the present study.

Another source of variability in cognitive-motor multitasking relates to prioritization strategies applied by individuals. As indicated in previous studies, complex multitasking environments may lead to a prioritization of one task over the other (Doumas et al., 2008). That is, the cognitive task receives priority over the postural task or vice versa. While older adults with cognitive impairments were found to prioritize the postural control task to avoid falling (i.e., posture first strategy; Rapp et al., 2006), this strategy of resource allocation does not seem to apply to younger adults as the risk of falling is almost negligible in this population (Granacher et al., 2011). In contrast, our results indicate that those young adults who operated at the limits of their resources rather focused on the performance of the cognitive task at the cost of impaired balance performance.

Additionally, the mean negative postural performance costs suggest that there was slightly greater postural sway in our sample in the posture only task, which was reduced when the demanding cognitive tasks were performed concurrently. There are various studies that report improved postural stability in postural-cognitive dual-task settings as compared to single postural tasks in young adults (Andersson et al., 2002; Riley et al., 2003). Task-specific changes in the direction of attention from an internal focus on the own body movement in the postural single task to the processing of visual and auditory stimuli in the cognitive-postural dual and triple tasks might provide one explanation for this effect. As suggested in the context of the 'constrained action hypothesis' (Wulf and Prinz, 2001; McNevin and Wulf, 2002; Wulf et al., 2004), focussing on the body movements might intervene with automatic postural control processes that maintain stable posture otherwise (Vuillerme and Nafati, 2007). This efficient automatic processing mode for the balance task might be re-established when attention is bound to the demanding cognitive tasks, thus leading to negative performance costs in the postural task. A combination of manipulations of attentional focus with neuroscientific measures might shed further light on these mechanisms in future studies.

Our fMRI results confirm previous findings of dual-task-specific neural activations in lateral fronto-parietal areas (D'Esposito et al., 1995; Schubert and Szameitat, 2003; Stelzel et al., 2006). Particularly activity in the lPFC has been related to dual-task-related increases in working memory load as well as processes associated with the coordination of the processing order of temporally overlapping tasks (Szameitat et al., 2002). The reported results of the present study do not allow to separate, whether individuals engage the right lPFC region more to deal with the higher working memory load or the flexible coordination demands for temporally overlapping tasks. Our previous study, which explicitly aimed at dissociating regions associated with load vs. coordination (Stelzel et al., 2008) suggests that regions in more anterior parts of the lPFC are rather related to dual-task coordination as compared to working-memory load associated with the number of relevant task rules. Also, further studies with other cognitive control paradigms suggest a role of the mid-lPFC in resolving interference in conflict situations (Botvinick et al., 2001; Miller and Cohen, 2001) but also related to high working memory load (Rypma et al., 1999; Curtis and D'Esposito, 2003; Nee et al., 2013). Future studies should specify this issue for cognitive-motor tasks, for example by varying the degree of temporal and structural overlap between cognitive and postural tasks.

A recent fMRI study directly assessed motor-cognitive dual-tasking in young and old adults using a simulated balance task concurrently with a calculation task (Papegaaij et al., 2017). Age-related differences in the up-regulation of activity from single to dual tasks were shown in the right insular cortex. However, no dual-task-specific activity was present for the applied dual task in that study. This suggests that task performance might not have involved higher working memory load or additional coordination processes, which in turn might be subject to inter-individual variability to a higher degree and thus might underly brain-behavior correlations. The cognitive dual task applied in our study revealed such dual-task-specific activity. Still, the association with postural sway remains an indirect one, as brain and behavioral measures were obtained in different sessions. This reflects the trade-off between using a naturalistic whole body balance task and obtaining anatomically precise online imaging data, which currently has to be resolved depending on the specific research question.

In contrast to studies with old adults, we did not find any robust interference effects in cognitive (i.e., in terms of p(hit)-p(false alarm)) or in balance performance on the group level. Only the RT data indicate that depending on the task load in the cognitive task (single vs. dual one-back task), interference with a postural task arises. When comparing RTs between the dual one-back task and the single one-back task dual-task costs were greater when the additional postural task was performed on the force plate than during MRI measurement. However, re-test effects cannot be excluded as an explanation for these differences in dual-task costs, as the MRI session took place after the force plate session for all participants. Previous studies on cognitive-motor interference mostly focused on old adults with fairly robust interference effects across studies (Woollacott and Shumway-Cook, 2002; Rapp et al., 2006; Granacher et al., 2011; Boisgontier et al., 2013). Findings in young adults are generally less consistent. While some studies showed cognitive-motor interference on a behavioral and a neural level in young adults (Holtzer et al., 2011; Zhou et al., 2014; Fujita et al., 2016), others failed to do so (Beurskens et al., 2014). Direct comparisons of the young and the aging brain have shown that old adults tend to show higher lPFC activity during working-memory tasks at lower objective loads compared to younger adults (Cappell et al., 2010). These findings suggest that due to degenerative processes, older adults might consistently engage additional resources (compensation-related utilization of neural circuits hypothesis, CRUNCH) to meet task demands (Reuter-Lorenz and Cappell, 2008). The resulting overactivation may have led to more stable results in the older population. The increased recruitment of right lPFC in young adults in the present study, suggests that also in the young population, some individuals might apply such compensatory processes to maintain an adequate performance level while others do not. The right lPFC thus might be a region that is recruited flexibly when individuals act at their capacity limits to support successful task performance under high load.

In sum, the present study allows preliminary insights into neural underpinnings of cognitive dual tasking in relation to balance performance in younger adults and suggests a possible mechanism, i.e., compensatory activity in right lPFC, that may explain a portion of variance in individual differences of balance performance. Characterizing the mechanisms of intra- and inter-individual differences in flexible resource allocation seems to be highly relevant for designing training procedures in impaired young and old adults. However, more research is needed to further understand personal as well as task factors that influence these individual differences.

LIMITATIONS AND FUTURE DIRECTIONS

Several limitations need to be considered when interpreting the results of this study. First, due to technical constraints, it was not possible to obtain data from the postural tasks during MRI testing. Even though we kept the tasks inside and outside the MRI as similar as possible, we were not able to show a direct relationship of the assumed compensatory recruitment of lPFC and CoP displacement. The shown association in the right lPFC might reflect the suggested common recruitment of this region for purely cognitive and cognitive-postural multitasking. Alternatively, as postural control has been associated with several other cortical and subcortical regions before, the shown association might be related to the extensive connectivity of the lPFC with other regions in terms of distant connectivity effects and thus be related to activity in other regions as well. Whether the right lPFC reflects dual-task specific processes (i.e., dual-task coordination or higher working memory load) or more general processes related to the allocation of limited resources cannot be inferred from our study and should be further addressed in the future.

Second, our sample was relatively small and replication in a larger sample would be important. With the advancement of neuroimaging techniques, a direct measurement of neural correlates of cognitive-motor multitasking interference may become feasible in future research.

Third, although we covered a range of input stimuli and output responses in the cognitive task, we do not have enough data to make conclusions about the generality of the shown association in the right lPFC. Also, differences between postural tasks and gait task should be further compared in future studies.

Regarding the implications for future training studies, our previous cognitive training study (Heinzel et al., 2016), indicated that over-activation in the right lPFC declined after 12 sessions of adaptive *n*-back working memory training. To present, however, it remains unclear if training-related alterations in lPFC may facilitate postural control performance likewise. Furthermore, it needs to be studied in future investigations, which specific training regimes lead to improvements in both cognitive performance and postural control. Possibly, an individualized motor-cognitive dual-task training that integrates multimodal diagnostic and evaluative parameters might be an effective approach.

CONCLUSION

The current study investigated brain activation patterns during the performance of a cognitive dual task compared to a single task by using fMRI. In a second session outside the MRI scanner, the same task was applied using a postural control setting. Behavioral results of the cognitive dual task showed that RT but not performance level was affected by an additional postural task, indicating neural compensatory mechanisms. FMRI findings support this notion as increased lPFC activity was related to larger postural sway while cognitive task performance was kept at a comparable level. Findings of this study may improve our understanding of the underlying neural mechanisms during the performance of complex motor-cognitive multitask situations. Knowledge from this study could be used and implemented in training studies.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

This work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG, priority program SPP 1772: grants GR 3997/4-1, HE 7464/1-1, and RA 1047/4-1). The authors would like to acknowledge that the Open Access Publishing Fund of the University of Potsdam supported publication of this work.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 25 June 2018
doi: 10.3389/fpsyg.2018.01031

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Dual-Task Processing With Identical Stimulus and Response Sets: Assessing the Importance of Task Representation in Dual-Task Interference

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OPEN ACCESS

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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: 05 March 2018
Accepted: 31 May 2018
Published: 25 June 2018

Citation:
Schumacher EH, Cookson SL, Smith DM, Nguyen TVN, Sultan Z, Reuben KE and Hazeltine E (2018) Dual-Task Processing With Identical Stimulus and Response Sets: Assessing the Importance of Task Representation in Dual-Task Interference. Front. Psychol. 9:1031. doi: 10.3389/fpsyg.2018.01031

Limitations in our ability to produce two responses at the same time – that is, dual-task interference – are typically measured by comparing performance when two stimuli are presented and two responses are made in close temporal proximity to when a single stimulus is presented and a single response is made. While straightforward, this approach leaves open multiple possible sources for observed differences. For example, on dual-task trials, it is typically necessary to identify two stimuli nearly simultaneously, whereas on typical single-task trials, only one stimulus is presented at a time. These processes are different from selecting and producing two distinct responses and complicate the interpretation of dual- and single-task performance differences. Ideally, performance when two tasks are executed should be compared to conditions in which only a single task is executed, while holding constant all other stimuli, response, and control processing. We introduce an alternative dual-task procedure designed to approach this ideal. It holds stimulus processing constant while manipulating the number of "tasks." Participants produced unimanual or bimanual responses to pairs of stimuli. For one set of stimuli (two-task set), the mappings were organized so an image of a face and a building were mapped to particular responses (including no response) on the left or right hands. For the other set of stimuli (one-task set), the stimuli indicated the same set of responses, but there was not a one-to-one mapping between the individual stimuli and responses. Instead, each stimulus pair had to be considered together to determine the appropriate unimanual or bimanual response. While the stimulus pairs were highly similar and the responses identical across the two conditions, performance was strikingly different. For the two-task set condition, bimanual responses were made more slowly than unimanual responses, reflecting typical dual-task interference, whereas for the one-task set, unimanual responses were made more slowly than bimanual. These findings indicate that dual-task costs occur, at least in part, because of the interfering effects of task representation rather than simply the additional stimulus, response, or other processing typically required on dual-task trials.

Keywords: cognitive control mechanisms, mental representation, multi-task learning, psychological refractory period, response selection

INTRODUCTION

In daily life, we must often process multiple stimuli and make multiple responses in close temporal proximity, which often produces a substantial decrease in performance on one or more of the tasks performed. This so-called multi-task (or dual-task) interference has been the subject of a large number of studies over the past 50 years (for review see Pashler, 1994). Nearly all of this research involves varying the overlap between the performance of one set of stimulus-response (S–R) mappings with a different set. For example, a popular procedure for studying dual-task interference is the psychological refractory period (PRP) procedure (e.g., Welford, 1952; Pashler, 1984). This procedure involves varying the stimulus-onset asynchrony (SOA) between stimuli associated with two distinct S–R mapping sets (tasks) and measuring the decrease in task performance as SOA decreases. This decrease in performance (i.e., dual-task cost) is hypothesized to be due to processing delays caused by the task overlap. The PRP procedure has been a useful technique for identifying the locus of dual-task interference when it exists (McCann and Johnston, 1992; Schumacher et al., 1999) – in response selection processes (i.e., the mental operations that associate task-related responses to current stimuli).

Despite the fruitfulness of this and other dual-task procedures, they have some limitations for identifying *task-related*, versus other, sources of interference. An implicit assumption with most, if not all, dual-task procedures is that adding one or more S–R mapping sets is equivalent to adding a task. Therefore, any decrease in performance due to increased temporal overlap between the performance of the S–R mapping sets is *dual-task* interference. There is a good reason for this assumption. However, processing of the additional stimuli or responses, or other control processes may also interfere with performance regardless of the participants' internal task representation.

Furthermore, we have shown that changing the temporal overlap between the tasks (e.g., simultaneous stimulus presentation) and the implicit and explicit priorities between them can demonstrate dual-task costs not strictly related to structural limitations in multi-tasking ability (Schumacher et al., 2001; Hazeltine et al., 2002; but see Byrne and Anderson, 2001; Anderson et al., 2005). However, simultaneous presentation of multiple-task stimuli exasperates the problem of isolating the interfering effect of task-related overlap. Thus, while the PRP procedure has effectively demonstrated that some task processes (e.g., stimulus identification) can be performed in parallel whereas others (viz., response selection) are often performed serially for distinct tasks, there is a serious limitation. Several studies (e.g., Schumacher et al., 2001; Hazeltine et al., 2002) have demonstrated that prioritizing one of the tasks and varying the SOA can produce dual-task interference that is not observed when participants perform the tasks simultaneously under other conditions. That is, the demands of the PRP procedure appear to produce interference that reflects control processes rather than structural capacity limitations. For example, Schumacher et al. (2001) showed that two tasks that could be performed without significant dual-task costs when the stimuli were presented simultaneously nonetheless produced large dual-task costs when the SOA was varied (Halvorson et al., 2013). Thus, while data from this approach likely reveal how the timing of task processes can be controlled, they may be less informative about the magnitude of interference between multiple task representations.

Here we describe a novel experimental procedure that overcomes this limitation and allows us to investigate the interference associated with performing two tasks unconfounded by the potential interference of processing multiple stimuli and responses. In this *task manipulation* procedure, participants make manual responses with both hands to the presentation of a face and building image. Some of the stimuli require responses and others do not. Participants perform two conditions. In the independent condition, the S–R mappings for the faces and places are independent of each other (i.e., the correct response for one does not depend on the other). In the relational condition, the S–R mappings include combinations of face and place stimuli (i.e., the correct responses are based on both stimuli). Because some stimuli for each condition are associated with no responses, each condition includes trials with both one (unimanual) and two responses (bimanual).

Critically, with this approach, we hold constant the number of stimuli presented on each trial and vary the number of responses. Because each condition has unimanual and bimanual response trials, it is possible to compute dual-task costs for them separately. We hypothesize that this manipulation of the S–R mapping conditions will produce a difference in the number of tasks participants think they are performing. That is, in the independent condition, participants will perform two tasks when there are two responses and one task when there is one response. Thus, reaction times (RTs) should be longer for stimuli that require two responses. In contrast, in the relational condition, participants will perform one task (which involves integrating two stimuli) no matter how many responses are produced, so RT should not depend on the number of responses. That is, the only difference between the conditions is whether participants represent the face and building stimuli as associated with separate S–R mapping sets or two tasks (viz., in the independent condition) or as part of a larger related S–R mapping set or single task (viz., in the relational condition).

The definition of "task" is often not made explicit in the literature. It may refer both to the activities required of the participant in an experiment as well as the participants' internal representation of those activities. While there is often complete overlap between those definitions in most experiments, here we make a distinction between participants' behavior and how they represent that behavior. Fundamentally, this is a question about how task representation affects performance. There are many theories for how information is represented and how its representation may affect behavior. In the 1980s, Norman and Shallice (1986) outlined how mental schema (complex associations between stimuli and responses) may guide behavior with and without the help of a supervisory attentional system. Kahneman et al. (1992) proposed that visual perception involved the formation of *object files*, described how attention may be allocated to task-relevant features to bind representations. Building on this idea, Hommel (1998, 2004) suggested that response selection involved the formation of *event files*, that included episodic information about both stimuli and responses. Recently, Schumacher and Hazeltine (2016), Hazeltine and Schumacher (2016) proposed the need to include another level in this representational hierarchy – namely that of a task. These *task files* include associations between stimuli and responses, contextual information, internal goals, and other relevant task information. Importantly, boundaries between task files may segregate the effects of interference in response selection (e.g., Hazeltine et al., 2011).

Because this research involves the effects of task representations – and these representations must be learned (Wilson and Niv, 2012) – we had participants practice the conditions over three experimental sessions so that we could be confident that their task representations were stable before we investigated the effect on dual-task interference. Additionally, because pilot testing showed that the relational condition was more difficult than the independent condition and we wanted to compare performance at similar levels of accuracy, the relational condition was practiced more than the independent condition.

MATERIALS AND METHODS

Participants

Sixteen participants (age range: 18–29 years; nine female) participated in this experiment in partial fulfillment of a course requirement. This study was carried out in accordance with the recommendations of the Georgia Institute of Technology, Institutional Review Board. The protocol was approved by the Institutional Review Board. All participants gave written informed consent in accordance with the Declaration of Helsinki.

Stimuli

Six grayscale male face images were used from the AR Face Database (Martinez and Benavente, 1998). The images included the neck, shoulders, and hair of the models. Six grayscale images of buildings (places) were also used. Three of each image type were randomly assigned to the independent and relational conditions. For the independent condition, each of the three faces were assigned to the left middle-finger response, the left index-finger response, and to no response. Place images were assigned in a similar fashion to the right middle-finger, right index-finger, and no response. For the relational condition, the other set of face stimuli were assigned to the left middle, left index, and no response conditions and the other set of places was assigned to the right middle, right index, and no response conditions. **Table 1** shows the mappings for the independent and relational conditions. The difference between the conditions was that, for the independent condition, the left-hand, right-hand, and no responses were not associated with each other, but for the relational condition, the particular left-hand, right-hand, and no responses were determined by the pair of stimuli presented.

Procedure

The experiment consisted of three sessions collected on separate days within 1 week while participants lay supine in a "mock" magnetic resonance imaging scanner. After obtaining informed consent on Session 1, each session began by informing/reminding participants that they would perform two conditions. For each condition, two stimuli appeared simultaneously. A face stimulus appeared to the left of fixation and a place stimulus appeared to the right. The entire stimulus array subtended approximately 2° × 14° visual angle (vertical × horizontal). Participants responded by pressing buttons with the index and middle fingers of both hands (or made no response). In the relational condition, they were instructed to respond based on "how each pair of stimuli maps to each pair of responses. Neither stimulus alone will tell you anything about either response." In the independent condition, they were instructed that the "left stimulus will indicate left response and right stimulus will indicate right response." Participants were encouraged to respond to each stimulus as quickly and as accurately as possible. Participants then completed a self-paced training procedure of 26 trials where each face and place image was shown with its correct response. For this phase, each trial began with a 500 ms fixation presented in the center of the screen followed by the stimuli to the left of fixation with the correct responses for the left and right hand indicated below the stimuli. The feedback display array is shown in **Table 1**. This display remained onscreen until participants pressed a key to advance to the next trial. The training began with the relational condition.

After obtaining informed consent and initial training on Session 1, Sessions 1 and 2 were identical. Both sessions

TABLE 1 | Stimulus-response mappings for the two experimental conditions.

	Independent condition			
	Left middle	**Left index**	**Right middle**	**Right index**
Face1–Place1	X	–	X	–
Face1–Place2	X	–	–	X
Face1–Place3	X	–	–	–
Face2–Place1	–	X	X	–
Face2–Place2	–	X	–	X
Face2–Place3	–	X	–	–
Face3–Place1	–	–	X	–
Face3–Place2	–	–	–	X
Face3–Place3	–	–	–	–
	Relational condition			
Face1–Place1	X	–	X	–
Face1–Place2	–	–	–	–
Face1–Place3	–	X	–	X
Face2–Place1	–	X	–	–
Face2–Place2	X	–	–	X
Face2–Place3	–	–	X	–
Face3–Place1	–	–	–	X
Face3–Place2	–	X	X	–
Face3–Place3	X	–	–	–

The X in each column indicates the correct response given the stimulus pair presented. For the independent condition, the correct response for one stimulus type does not depend on the other. For the relational condition, the correct response is determined by the pair of stimuli presented. The X's and dashes were presented to participants as feedback.

included 12 blocks: eight of the relational condition and four of the independent, randomized so that two relational blocks and one independent block occurred every three blocks (super block). After every super block, participants went through the initial self-paced training procedure again. Participants received feedback about their left- and right-hand accuracy and mean RT after every block, which remained onscreen until participants were ready to begin the next block. Participants also received feedback showing the correct mapping for 1000 ms after every incorrect trial. Session 3 was identical to Sessions 1 and 2 except participants performed six blocks of each condition and did not receive trial-level feedback after errors. The first block type was selected randomly and then alternated for the rest of the session.

Each block included 18 trials (two replications of each stimulus–response pair). To control for anticipation effects, each block also included eight catch trials where no stimuli appeared and the fixation cross remained onscreen for 2500 ms. Each experiment trial began with a fixation cross presented in the center of the screen alone for 500 ms. The stimulus pair then appeared with the fixation cross for 2000 ms. Finally, the stimuli disappeared and the fixation cross remained onscreen for a 1000 ms inter-trial interval. Participants responses were collected during the stimulus display period.

RESULTS

The critical test for the effect of task representation on dual-task processing is in Session 3, once participants had learned the tasks. However, to investigate how these task-representational structures change through practice, we also report the data from the first two sessions. That is, we wished to determine whether the two conditions, which involved nearly identical stimulus sets and identical responses, showed similar learning rates. We report the data from the first two sessions separately from Session 3 because they used a slightly different protocol and performance stabilized by the third session.

Sessions 1 and 2

Reaction Time

The mean RT data from Sessions 1 and 2 are shown in **Figure 1**. Trials with an incorrect response or less than 200 ms (23% total) were removed from the RT analysis. The remaining data were analyzed with a 2 × 2 × 2 × 4 within-subjects ANOVA with Condition (Relational and Independent), Response (Unimanual and Bimanual), Session (Sessions 1 and 2), and Super Block (1–4) as factors. Early in Session 1, three participants made errors on every trial in a block so their data are excluded from analysis. The data violated the assumption of sphericity so the Huynh–Feldt correction was used for all comparisons. There were significant main effects of both Session and Super Block [$F(1,12) = 39.45$, $p < 0.001$, MSE = 58,460.18, $\eta^2 = 0.767$ and $F(2.84,34.10) = 13.02$, $p < 0.001$, MSE = 19,605.34, $\eta^2 = 0.520$, respectively] such that participants got faster with practice. There were only two significant interactions. The interaction between Response and Session, $F(1,12) = 5.86$, $p < 0.05$, MSE = 13,584.78, $\eta^2 = 0.328$, showed that Unimanual mean RT improved more with practice (181 ms) than Bimanual mean RT (121 ms). The interaction between Condition, Super Block, and Session, $F(2.38,28.55) = 3.17$, $p < 0.05$, MSE = 17,914.47, $\eta^2 = 0.209$, showed that Independent condition mean RT decreased across all blocks but Relational condition mean RT did not start decreasing until Super Block 4 in Session 1.

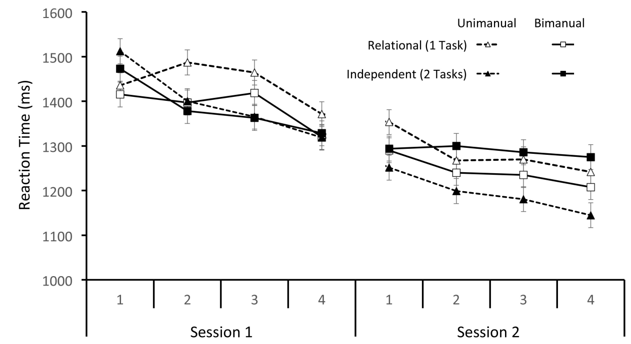

FIGURE 1 | Mean RTs separated by the Mapping and Response conditions across Super Blocks for Sessions 1 and 2.

Accuracy

The mean accuracy data from Sessions 1 and 2 are shown in **Table 2**. To control for possible violations of normality, the accuracy data were transformed using an arcsine transformation ($\arcsin(\sqrt{x})$) (Sokal and Rohlf, 1995); and analyzed with a 2 × 3 × 2 × 4 within-subjects ANOVA with Condition (Relational and Independent), Response (Unimanual, Bimanual, and No Response), Session (Sessions 1 and 2), and Super Block (1–4) as factors. The data violated the assumption of sphericity so the Huynh–Feldt correction was used for all comparisons. Only significant effects will be described here. There were significant main effects of Task, Response, Super Block, and Session: $F(1,15) = 31.21$, $p < 0.001$, MSE = 0.24, $\eta^2 = 0.675$; $F(1.80,27.06) = 55.44$, $p < 0.001$, MSE = 0.18, $\eta^2 = 0.787$; $F(2.82,42.36) = 88.52$, $p < 0.001$, MSE = 0.06, $\eta^2 = 0.86$; and $F(1,15) = 114.84$, $p < 0.001$, MSE = 0.27, $\eta^2 = 0.884$, respectively. Accuracy was higher for the Independent condition than the Relational condition (84% vs. 70%). No Response, Bimanual, and Unimanual were significantly different (89%, 74%, and 68%, respectively). Accuracy increased across Super Blocks 1–4 (62%, 74%, 83%, and 89%, respectively) and across Sessions 1 and 2 (63% vs. 91%). There were also several significant interactions. The interaction between Condition and Response was significant, $F(2,30) = 19.89$, $p < 0.001$, MSE = 0.08, $\eta^2 = 0.57$, such that accuracy for the Relational condition varied across response types more than the Independent condition. The interaction between Response and Super Block was also significant, $F(3.17,47.49) = 4.13$, $p < 0.05$, MSE = 0.07, $\eta^2 = 0.22$, such that accuracy for the No Response condition improved

TABLE 2 | Mean accuracy across sessions.

	Session 1 Super block				Session 2 Super block				Session 3
Mapping condition	1	2	3	4	1	2	3	4	
Relational (1 task) unimanual	10	20	37	54	67	78	86	87	90
Relational (1 task) bimanual	19	35	62	77	81	84	85	89	91
Relational (1 task) no response	48	74	90	95	99	98	98	98	99
Independent (2 tasks) unimanual	39	64	80	89	94	94	97	96	95
Independent (2 tasks) bimanual	46	65	80	92	88	88	92	97	94
Independent (2 tasks) no response	64	89	86	95	95	100	98	97	99

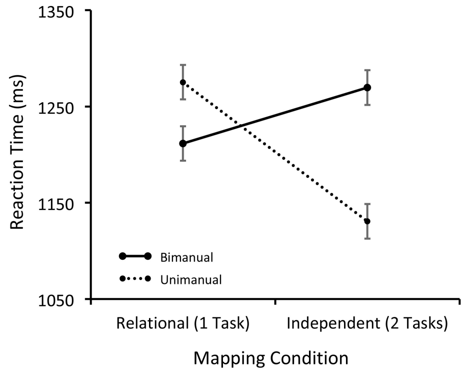

FIGURE 2 | Mean RTs separated by the Mapping and Response conditions for Session 3.

more slowly than the other conditions. The interactions between Condition and Session [$F(1,15) = 14.92$, $p < 0.05$, MSE = 0.09, $\eta^2 = 0.50$] and Response and Session [$F(1.55, 23.25) = 9.58$, $p < 0.05$, MSE = 0.12, $\eta^2 = 0.39$] were also significant, such that accuracy for the Relational condition and the Unimanual condition improved the most from Session 1 to Session 2. The interaction between Super Block and Session [$F(3,45) = 33.40$, $p < 0.001$, MSE = 0.06, $\eta^2 = 0.69$] was significant, such that accuracies improved more in Session 1 than Session 2. Finally, there was a significant four-way interaction between Condition, Response, Super Block, and Session, $F(5.73,85.87) = 3.54$, $p < 0.05$, MSE = 0.03, $\eta^2 = 0.19$. Accuracies for the Unimanual and Bimanual responses in the Relational condition were quite low in Session 1 but improved so that accuracies across all conditions were similar by the end of Session 2.

Session 3

Reaction Time

Trials with incorrect responses or less than 200 ms (5% overall) were removed from the RT analysis. The mean RTs for the remaining data are shown in **Figure 2** and were analyzed with a 2 × 2 within-subjects ANOVA with Condition (Relational and Independent) and Response (Unimanual and Bimanual) as factors. Neither the effect of Condition nor Response was significant: $F(1,15) = 2.43$, $p = 0.14$, MSE = 12,332.21, $F(1,15) = 3.48$, $p = 0.08$, MSE = 6491.06, respectively. The Condition by Response interaction, however, was significant: $F(1,15) = 32.37$, $p < 0.001$, MSE = 5069.30, $\eta^2 = 0.683$. Critically, for the Independent condition, unimanual responses were produced significantly faster than bimanual responses [$t(15) = 4.93$, $p < 0.001$], but for the Relational condition, the unimanual responses were significantly slower than bimanual ones [$t(15) = 2.50$, $p < 0.05$]. Additionally, bimanual responses did not differ between the two mapping conditions [$t(15) = 1.56$, $p = 0.14$], but unimanual responses did [$t(15) = 5.13$, $p < 0.001$].

Accuracy

Mean accuracies are shown in **Table 2**. To control for possible violations of normality, the accuracy data were transformed using an arcsine transformation ($\arcsin(\sqrt{x})$) (Sokal and Rohlf, 1995). The transformed data were analyzed with a 2 × 3 within-subjects ANOVA with Condition (Relational and Independent) and Response (Unimanual, Bimanual, and No Response) as factors. The data violated the assumption of sphericity so the Huynh–Feldt correction was used for all comparisons. The only significant effect was for Response: $F(1.3,19.7) = 49.23$, $p < 0.001$, MSE = 0.01, $\eta^2 = 0.766$. Participants were slightly less accurate on the Relational than the Independent condition. Neither the effect of Condition nor the interaction between Condition and Response was significant: $F(1,15) = 3.478$, $p = 0.08$, MSE = 0.20, $F(2,30) = 2.59$, $p = 0.09$, MSE = 0.01, respectively.

DISCUSSION

The critical test of the hypothesis that task representation affects dual-task processing is tested in the data from Session 3, once participants have learned the task representations. Here despite the similarity between the stimulus and response sets used in the relational and independent conditions, participants showed distinct patterns of behavior depending on whether one or two responses were required. There was no effect of mapping or response condition on RT, but there was significant interaction between mapping condition and response (**Figure 2**). When participants considered the face and place stimuli to be part of separate task representations (the independent condition) they showed dual-task interference when making two responses, but when they considered the stimuli to be part of the same task representation (the relational condition) they did not, despite the similarity in the stimuli and responses in the two conditions. That is, performance improved when they only had to make a single response versus when they had to make two responses for the independent condition but not for the relational condition. Thus, there was a typical dual-task cost of making two manual responses to simultaneously presented stimuli versus making one manual response (e.g., Schumacher et al., 2001; Hazeltine et al., 2002), but this interference disappeared under identical stimulus and response conditions, when participants represented the stimuli and responses as part of one task. These data show, unequivocally, that the way in which people represent tasks affects how they behave.

There are several advantages to studying dual-task interference using a method like the one described here. Using simultaneous presentation of the stimuli and equal priority instructions (e.g., Schumacher et al., 2001; Hazeltine et al., 2002) may discourage strategic dual-task slowing (c.f., Meyer and Kieras, 1997a,b). However, the more novel contribution of this procedure is the way it isolates the interfering effects of task representations across the two mapping conditions. The between condition comparisons allow for the manipulation of the number of performed tasks while keeping the number of stimuli and responses constant.

Interpreting data from conventional approaches require one to assume the stimulus, response, and/or other control processing does not change across conditions. These ancillary processing assumptions are not required with the current approach. This may be particularly useful when studying the neural effects of dual-task interference where lack of control over stimulus, response, and control processing may lead to extraneous and difficult to interpret patterns of brain activity. For example, many dual-task neuroimaging studies associate prefrontal and parietal regions for dual-task processing (for a review, see Marois and Ivanoff, 2005), however others do not (e.g., Jiang et al., 2004) and Nijboer et al. (2014) suggest there is no specific region associated with dual-task processing, rather dual-task interference is due to overlap in the network of brain regions involved in task processing. This inconsistency may be caused by the poor control over the processing requirements across single- and dual-task conditions in those studies.

Although not the focus of the current research, the data obtained during training are also informative. Across Sessions 1 and 2, RTs decreased for both the relational and independent conditions. Accuracies were quite different – especially in Session 1 – between the two conditions. Accuracy was worse in the relational condition than the independent condition (despite the increased practice with this condition) through most of Sessions 1 and 2 – though accuracies were above 85% by the end of Session 2 for all conditions. This shows that the way participants represented the S–R pairs affected their ability to learn the responses. It was easier to learn the S–R pairs when they were part of separate task files than when they were part of the same one.

Despite the potential benefit of this procedure for studying dual-task interference, there are several limitations with the current research. For the relational condition, the RTs in Session 3 are closer to the bimanual independent RTs than the unimanual independent RTs (**Figure 2**). Therefore, it could be argued that both response conditions in the relational condition were affected by dual-task interference. We think this is unlikely because one would expect the RTs for the relational condition to be longer than the independent condition because it requires participants to represent a larger S–R mapping set (nine S–R pairs vs. three pairs for each task).

Another potential limitation is that the unimanual responses were significantly slower than the bimanual responses for the Relational condition on Session 3. This dual-task benefit was not predicted and it is difficult to know how to interpret it. The bimanual responses were not significantly different between the two mapping conditions so the difference between the unimanual and bimanual responses for the relational condition may be spurious. Alternatively, participants may have had a bias for making two responses in the relational condition and this may have caused additional slowing on unimanual trials. A third possibility is that the relationship between the participants' task representation and stimulus display may produce more complex behavioral outcomes than simply the presence or absence of dual-task interference. Wickens and Carswell (1995) have proposed a proximity compatibility principle describing how factors such as the physical similarity between stimuli may facilitate or disrupt performance depending on whether participants have to integrate the stimuli (as in the relational condition) or respond to them independently. This principle is typically applied to complex displays (e.g., airplane cockpits) so more research is necessary to understand how they apply to the current procedure.

Finally, the present experiment is not able to identify the cause of the dual-task interference in the independent condition. It may be caused by bottlenecks in response selection or response production, or response grouping (Pashler, 1994). Nevertheless, the procedure described here demonstrates that performing two tasks produces interference even when the stimulus and response requirements are held constant. These data indicate that it is the requirement to maintain and select between two task sets that affect performance in dual-task situations and not only ancillary differences in stimulus and response processing. These results highlight the importance of considering task file representations when considering controlled processing requirements (c.f., Hazeltine and Schumacher, 2016; Schumacher and Hazeltine, 2016).

AUTHOR CONTRIBUTIONS

EH and ES conceived the research idea. DS, EH, ES, SC, and TN conducted the analyses. DS, EH, ES, KR, SC, TN, and ZS designed the experiment. EH, ES, and SC wrote the manuscript. DS, EH, ES, KR, SC, and TN edited the manuscript. DS, SC, KR, TN, and ZS collected the data.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 15 June 2018
doi: 10.3389/fpsyg.2018.00910

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Multitasking During Simulated Car Driving: A Comparison of Young and Older Persons

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Human multitasking is typically studied by repeatedly presenting two tasks, either sequentially (task switch paradigms) or overlapping in time (dual-task paradigms). This is different from everyday life, which typically presents an ever-changing sequence of many different tasks. Realistic multitasking therefore requires an ongoing orchestration of task switching and dual-tasking. Here we investigate whether the age-related decay of multitasking, which has been documented with pure task-switch and pure dual-task paradigms, can also be quantified with a more realistic car driving paradigm. 63 young (20–30 years of age) and 61 older (65–75 years of age) participants were tested in an immersive driving simulator. They followed a car that occasionally slowed down and concurrently executed a mixed sequence of loading tasks that differed with respect to their sensory input modality, cognitive requirements and motor output channel. In two control conditions, the car-following or the loading task were administered alone. Older participants drove more slowly, more laterally and more variably than young ones, and this age difference was accentuated in the multitask-condition, particularly if the loading task took participants' gaze and attention away from the road. In the latter case, 78% of older drivers veered off the road and 15% drove across the median. The corresponding values for young drivers were 40% and 0%, respectively. Our findings indicate that multitasking deteriorates in older age not only in typical laboratory paradigms, but also in paradigms that require orchestration of dual-tasking and task switching. They also indicate that older drivers are at a higher risk of causing an accident when they engage in a task that takes gaze and attention away from the road.

Keywords: task switching, dual-tasking, aging, cognitive-motor interference, ecological validity, virtual reality, car driving, multitasking

Edited by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *15 December 2017*
Accepted: *18 May 2018*
Published: *15 June 2018*

Citation:
Wechsler K, Drescher U, Janouch C, Haeger M, Voelcker-Rehage C and Bock O (2018) Multitasking During Simulated Car Driving: A Comparison of Young and Older Persons. Front. Psychol. 9:910. doi: 10.3389/fpsyg.2018.00910

INTRODUCTION

In everyday life, we often must perform multiple cognitive and motor tasks concurrently. For example, we steer a car along the road while watching for other traffic, responding to street signs and planning our route. As another example, we stroll on a sidewalk while avoiding obstacles, obeying traffic lights and chatting with another person. Experimental research about human multitasking began with a study by Jersild (1927), who reported that task performance deteriorates when two tasks are executed in an interleaved rather than in a blocked fashion. These performance decrements, later called "switching costs," were attributed to the effort involved in disengaging from one task and adjusting to another task (Rogers and Monsell, 1995). In another line of research, two tasks were presented simultaneously or with a small stimulus onset asynchrony (Telford, 1931), which again led to performance decrements, called "dual-task costs." The latter costs were attributed to a central processing bottleneck (Welford, 1952), task competition for a limited pool of attention (Kahneman, 1973) or competition for limited pools of specific processing resources (Wickens, 2002). These costs implicate a deterioration of performance, when the required attentional resources exceed the available ones. When participants have to handle very complex tasks or several tasks that require attention from the same pool, structural interferences impair the simultaneous handling of those tasks (Duncan et al., 1997). In real-life car driving, for example, a driver who passes a construction zone with narrow lanes must tightly control the car's lateral position while at the same time keeping his distance to the preceding car. This forces the driver to direct his gaze at two spatially distinct locations concurrently, which is physically not possible, i.e., structural interference emerges (Heuer, 1996). In contrast, driving in narrow lanes without a leading car while listening to traffic announcements should lead to less structural interference, because the tasks don't share sensory modalities.

Five decades of research provided indisputable evidence that abilities in cognitive (reviews in Craik, 1977; Verhaeghen et al., 2003) and motor-cognitive (Hahn et al., 2010; Beurskens and Bock, 2013) multitasking decline with advancing age. This age-related decline is not uniform, however. It affects mainly task combinations which draw heavily on working memory (Voelcker-Rehage et al., 2006; Voelcker-Rehage and Alberts, 2007; Chu et al., 2013) and/or visuo-spatial processing (Beurskens and Bock, 2012), and/or postural control (Boisgontier et al., 2013), and it emerges even if multitasking is limited to singular events such as an unexpected stimulus (Bock and Beurskens, 2011) or an unexpected error (Voelcker-Rehage et al., 2006). The decay of multitasking abilities in older age is also correlated with a decay of task-switching and memory-updating abilities (Kray and Lindenberger, 2000; Holtzer et al., 2005; Iersel et al., 2008; Liu-Ambrose et al., 2009), which suggests that it is at least partly due to an age-related impairment of executive functions.

It should be noted, that the age-related decline of multitasking abilities was observed in traditional laboratory paradigms and may not generalize unconditionally to real life. Laboratory research typically uses a limited number of well-defined stimuli (e.g., colored shapes on an otherwise blank screen), prescribes a limited number of elementary response alternatives (e.g., button presses) and associates those responses with no ecologically valid purpose. In contrast, everyday life offers an ever-changing flow of complex stimuli to which we respond by complex behavior in order to achieve a desirable goal. Furthermore, virtually all laboratory research was concerned with 'multi' tasking but actually presented only two tasks. This work therefore neglects the fact that in real life, we face an ever-changing sequence of concurrent tasks and must adjust to all of them in sequence. In other words, realistic multitasking incurs both dual-task costs and switching costs. Summing up, traditional laboratory paradigms suffer from behavioral impoverishment, lack of purpose and absence of the natural interplay between dual-tasking and task switching. The ecological validity (Chaytor and Schmitter-Edgecombe, 2003) of those paradigms may therefore be limited.

Several studies avoided behavioral impoverishment and lack of purpose by implementing realistic and immersive virtual-reality tasks such as car driving, street crossing or grocery shopping. Some of those studies dealt with dual-tasking: they combined virtual car driving or street crossing with a concurrent, cognitive or motor loading task. For example, simulated car driving has been combined with mobile texting (Drews et al., 2009), pattern detection or color memorizing (Cassavaugh and Kramer, 2009), and simulated street crossing with mobile internet use (Byington and Schwebel, 2013), listening to music or cellphone conversation (Neider and Kramer, 2011). The few studies which administered more than one concurrent task did so in separate blocks (Cassavaugh and Kramer, 2009; Neider and Kramer, 2011) and therefore still dealt with dual-tasking only; they didn't address the natural interplay of dual-tasking and task switching encountered in everyday life. The present research goes beyond those studies by including such an interplay: our participants drove in a car driving simulator and concurrently performed not just one repetitive loading task, but rather an ever-changing sequence of loading tasks that involved different stimulus modalities, different cognitive processes and different output channels. To our knowledge, ours is the first study to introduce such a multitude of intermixed loading tasks.

Earlier virtual-reality studies reported a range of performance deficits under dual-task conditions. Thus, braking reaction times increased (Lamble et al., 1999; Lee et al., 2002; Strayer et al., 2003), gap estimations became less optimal (Brown et al., 1969), steering wheel control deteriorated (Kubose et al., 2006) and drivers responded to road hazards less often (Horberry et al., 2006). Findings were similar when loading tasks were administered while participants drove a real car on a closed-road circuit (Chaparro et al., 2005). The detrimental effects of loading tasks persisted even when drivers were encouraged to ignore them and to prioritize car braking (Levy and Pashler, 2008). Some of the available studies on dual-tasking in virtual reality dealt with older participants (Chaparro et al., 2005; Horberry et al., 2006; Anstey and Wood, 2011), but they didn't sufficiently compare their performance to that of young persons. The effects of old age on realistic dual-tasking, let alone on the natural interplay of dual-tasking and task switching, are therefore still largely unknown. The main purpose of the present study was to close this gap in our knowledge.

It is well established that divided and selective attention deteriorate with advancing age (e.g., Rabbitt, 1965; McDowd and Shaw, 2000; review in Verhaeghen et al., 2003), especially when the tasks are complex (Zanto and Gazzaley, 2014) and that this downward trend is associated with poorer driving safety (Ball et al., 1993). It therefore is quite conceivable that the natural interplay of dual-tasking and task switching in realistic scenarios deteriorates as well. However, it has also been shown that age-related deficits observed in the laboratory may be absent under more natural conditions (Bock and Beurskens, 2010; Verhaeghen et al., 2012), possibly because older persons capitalize on their lifelong experience (Salthouse, 1984; Neider and Kramer, 2011). We therefore hypothesized that both young and older persons will show multitasking deficits when driving, that these deficits will be more pronounced when the loading task requires substantial visual processing and thus introduces structural interference, and that the magnitude of those deficits will be only moderately higher in older compared to young persons because of lifelong experience.

Summing up, our study is the first to compare young and older participants' driving skills when exposed to a natural interplay of dual-tasking and task switching.

MATERIALS AND METHODS

Participants

Sixty-three young (age 20–30 years; M = 23.17, SD = 2.83, females = 40) and 61 older (age 65–75 years; M = 69.97, SD = 2.96, females = 22) adults were recruited via postings at public places, social media, contacts with local senior networks as well as the website of the German Sport University Cologne and the Chemnitz University of Technology. Inclusion criteria were:

- A driving history of at least one trip per week during the last 6 months (self-report)
- No experience in multitasking research or simulator driving by self-report
- Good physical and mental health by self-report
- No history of stroke or brain surgery and no red-green color blindness by self-report
- A physician's health clearance based on an exercise ECG within the last 6 months
- Visual acuity better than 20/60 (as assessed by the Freiburg Vision Test "FrACT", Version 3.9.0); although the minimum requirement for a drivers' license is 20/40 in most jurisdictions, driving safety is not degraded with a visual acuity of 20/60 (Keeffe et al., 2002).

Those who met these criteria underwent screening tests to assure that they don't suffer from: cognitive impairment (assessed by the Mini-Mental State Examination; cutoff: 27/30 points), language comprehension deficits (assessed by the "Freiburger Sprachverständlichkeitstest"; cutoff: 50% word recognition at best hearing level) or obesity (cutoff: BMI $\geq$ 30).

The Edinburgh Handedness Inventory (cf. Oldfield, 1971) was used to determine hand dominance. Five Participants were left-handed, all others were right-handed. One participant was ambidextrous but used the right hand for the typing task. Persons who usually wore contact lenses, prescription glasses or hearing aids did so as well while participating in our study.

Participants were informed about the possibility to experience simulator sickness, and about their right to interrupt or abort the session at any time. Among the recruited persons, six young ones dropped out without giving a reason, three older ones because of simulator sickness and an older one because of reasons unrelated to our study. Registrations therefore were completed, and data were analyzed, from 63 young adults and 61 older ones.

This study was carried out in accordance with the recommendations of the Ethics Commission of the German Sport University with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Commission of the German Sport University. Participants received 15 € per session (60€ in total).

Driving Task

Figure 1 shows a schematic top view of the setup, **Figure 2** shows a photo of the realization and the environment. Participants sat in a conventional car seat in front of three 48″ TV screens, which rendered the driver's view of cockpit and surrounds with a total viewing angle of 195°. A steering wheel and pedal set (Logitech G27) were mounted in locations similar to a real car, and a numeric keypad ('K' in **Figure 1**) was mounted within easy reach. Participants wore a headset with microphone (shark zone H10, Sharkoon) not shown in **Figure 1**.

Commercially available driving simulator hard- and software (Carnetsoft® version 8.0) was used to display a softly winding rural road without traffic lights or intersections. The driving environment was realistically portrayed with road signs, buildings and other vehicles (cars, busses, and trucks) which traveled in the opposing lane at constant speed. The landscape contained animals, trees, bushes, fences, straw bales, mountains and clouds in a blue sky. Participants drove a VW Golf with automatic transmission, and had full front and side view out of the cockpit. The dashboard displayed the typical devices including a speedometer. Two side-view and one rear-view mirrors were located in the usual locations, and presented the expected views.

Participants were instructed to follow a lead car which drove at a constant speed of 70 km/h. At irregular intervals, the lead car approached a construction site or a speed-restricted zone and slowed down to 40 km/h within 7 s. It kept this speed for 6 s, and then returned within 9 s to 70 km/h. Thus, participants had to slow down in order to avoid a collision, and to speed up afterwards in order to keep up with the leading car. We will refer to this maneuver as 'braking task.' Each driving trip was 25.7 km long, included 10 braking tasks and took about 25 min to drive.

When drivers didn't keep up with the leading car and inter-vehicle distance exceeded 100 m, the leading car slowed down to 70% of the participants' current speed until inter-vehicle distance decreased to 50 m, and then sped up again. This ensured comparable inter-vehicle distances for all participants and conditions.

Loading Tasks

A battery of loading tasks was presented in a mixed order, at unpredictable times. Task presentation was identical for every participant. Tasks were modeled after natural activities, involved different sensory modalities and required different types of responses. A given type of any task was not presented twice in succession via the same modality. The sound volume of auditory stimuli was individually adjusted for each participant. Each of the three following types of task was presented 20 times during a driving trip: 10 times visually for 5 s in the middle of the

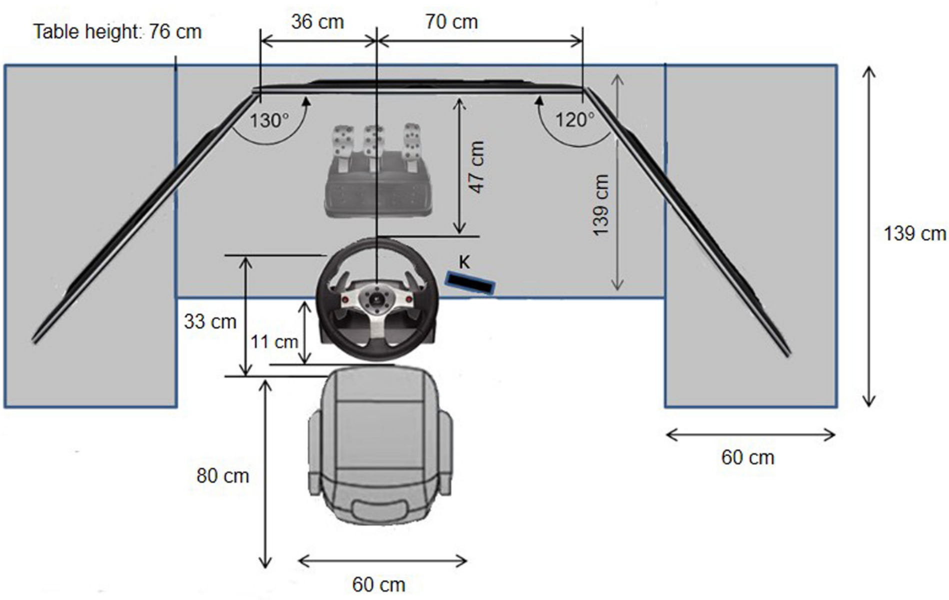

FIGURE 1 | Driving setup, Top view. Keypad marked with 'K,' three monitors (black color in the picture) lined up as shown on top of three tables (gray color in the picture). Central table made transparent in the picture to show pedals. Seat, steering wheel and pedals lined up as shown.

windshield and 10 times auditorily over headphones (Example in **Figure 3**).

- Typing: a three-digit number was presented, and participants responded by typing that number into the keypad. This task simulates operating, e.g., a radio receiver or GPS navigator.
- Reasoning: a question which couldn't be answered by "yes" or "no" was presented, e.g., "What would be an argument against the taxation of sugar?" Participants responded verbally, and their response was registered by the headset microphone. This task simulates conversation with a car passenger or via a hands-free mobile phone.
- Memory: In the visual version, participants passed a gas station equally often appearing on the right or left side of the road and were asked over headphones whether the displayed price for premium gas was the same as at the preceding gas station immediately after (Example in **Figure 4**). In the auditory version, participants heard a traffic announcement over headphones and were then asked whether the reported congestion (highway number, location, length) was the same as in the preceding traffic announcement. In both task versions, participants respond verbally "yes" or "no" into the headset microphone.

FIGURE 2 | Driving simulator environment.

Procedures

Each participant completed four experimental sessions on separate days, with at least 1 day off in-between. This took between 8 and 28 days, depending on the participants' availability. The first session included screening tests (to meet our inclusion criteria), driving simulator practice and practice of the loading tasks. Before the practice trials, participants received instructions and were encouraged to ask questions. Driving was practiced for 3–4 min, on the same course used for data collection. Loading tasks were practiced for 3–4 min on the same course as well, while the car drove in autopilot mode. The multitask condition (MT) was not practiced.

The subsequent three sessions were administered in an order that was balanced across participants. In one session, participants drove behind the leading car with no additional tasks (single-task driving, ST_D). In another session, they drove behind the leading car while concurrently responding to the loading tasks

FIGURE 3 | Screenshot out of the cockpit with visually displayed reasoning task.

FIGURE 4 | Screenshot out of the cockpit with visually displayed memory task.

(MT). In yet another session, the car drove in autopilot mode to provide a similar visual stimulation as in the other two sessions, and participants only responded to the loading tasks (ST_L). The driving course was identical in all three conditions. Before the practice trials and at the beginning of the 2nd, 3rd, and 4th session, the examiner read aloud the pertinent instructions and explained every task separately. (S)he then withdrew from the participants' view; during the remainder of the session, (s)he took notes and supervised the procedure without disturbing or interacting with the driver.

Participants also underwent cognitive and physical testing, and their street-crossing behavior was examined in a separate virtual-reality setup. This paper focuses on driving, a separate contribution in this issue deals with street crossing, and the other outcomes will be communicated later.

Data Analysis

Driving performance in MT was analyzed within road segments of interest. Each segment started with the presentation of a loading task and ended 1 s before presentation of the next loading task. Segment duration varied, in dependence on driving speed and loading-task distance, in the range 17.46 ± 2.45 s (Mean duration $\pm$ standard deviation). We adopted this particular definition of road segments in order to analyze driving performance even when responses required substantial time for pondering and verbalizing. On rare occasions, reasoning took longer than the duration of the pertinent road segment; we then decided case by case whether the response was substantially completed and if not, marked it as 'invalid.'

Since the driving course was identical in all three conditions, we could analyze participants' performance in each condition within the same road segments (i.e., same road curvature and visual scenery). However, this similarity of the driving environment does not extend to the individual loading tasks: it is conceivable that on the average, one loading task was presented on curvier road segments and/or in a more cluttered visual scenery than another loading task. Differences between tasks are therefore confounded by differences between road conditions. By the same token, differences between modalities are confounded by differences between road conditions. Scattering of loading tasks along therefore added to the realism of our paradigm, but hinders comparisons between tasks and modalities.

The simulator software registered a range of continuous signals at a rate of 10 Hz. Among them were the lateral position of the driven car (0 m: car centered in its lane; <-0.78 m: right wheels off the road), and its distance from the lead car (0 m: bumpers touch). From these signals, we calculated the following parameters for each road segment of interest:

- *Mean velocity*
- *Standard deviation of velocity (SD velocity)*
- *Mean lateral position*
- *Standard deviation of the lateral position (SD lateral position).*

Furthermore, we calculated the following parameters for the typing and the memory task:

- *Reaction time (RT): Interval between task presentation and response onset*
- *Correctness (COR): Proportion of all correct key presses in the typing task [0.00 (all wrong), 0.33 (one correct), 0.67 (two correct) or 1.00 (all correct), response correctness in the memory task (0 (wrong) or 1 (correct)].*

Reaction time and COR in the typing task were determined by a software algorithm. RT in both other tasks was determined manually, by setting a cursor in the visually displayed voice tracks. COR in both other tasks was determined by listening to the voice tracks. We noticed during data analysis that in the memory task, older participants often started to respond even before the verbal question was completed. We therefore decided to exclude RT in the memory task from further analyses. All other parameters were averaged across the 10 repetitions of each task, excluding outliers as identified by the $\pm$ 3.29 SD criterion (Tabachnick et al., 2001).

Statistical Analyses

Averaged scores were submitted to four-way analyses of variance (ANOVAs) with repeated measures on the factors Condition (ST and MT), Task (memory, reasoning, and typing) and Modality (visual and auditory) and the

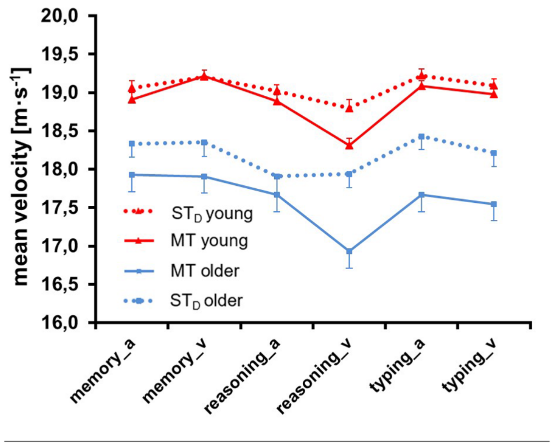

FIGURE 5 | Mean velocity ± SE of both age groups in single task (ST_D) and multitask (MT) conditions. Memory, reasoning and typing task were presented auditorily (_a) and visually (_v).

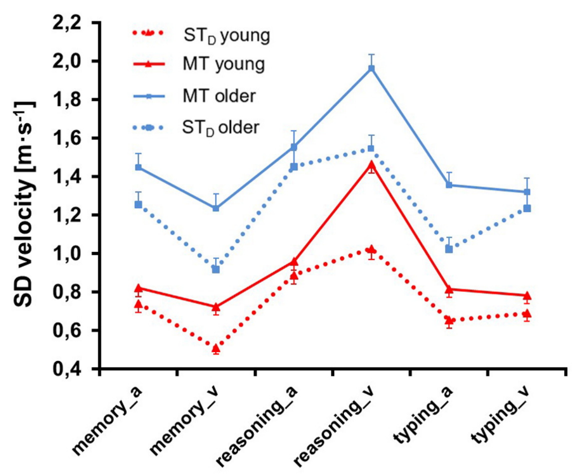

FIGURE 6 | Standard deviation of velocity ± SE of both age groups in single task (ST_D) and multitask (MT) conditions. Memory, reasoning and typing task were presented auditorily (_a) and visually (_v).

between-factor Group (young and older). We interpreted η_p^2 values < 0.06 as small, 0.06–0.14 as medium and >0.14 as large effects (Cohen, 1992). $P < 0.05$ was set for statistical significance. When the assumption of sphericity was violated in Mauchly's tests, degrees of freedom were Greenhouse-Geisser corrected. We used IBM SPSS Statistics, version 25 (IBM Corp., Armonk, NY, United States) for those calculations.

RESULTS

Driving Task

Figure 5 illustrates the driving parameter *mean velocity* of both age groups in ST_D and in MT, separately for all six combinations of loading task and modality. ANOVA (see **Table 1**) yielded a significant main effect for Condition: participants drove more slowly in MT compared to ST_D ($F = 12.07$, $p = 0.00$, $\eta_p^2 = 0.09$, df = 1, 122). The mean difference between MT and ST_D was 1.35 ± 0.74 km/h. Slowing was least pronounced for the memory task and most pronounced for the reasoning task (significant ANOVA effect for Condition × Task), particularly when the latter was presented visually (significance for Condition × Modality, Task × Modality and Condition × Task × Modality). We further found a significant main effect for Group: older participants drove more slowly than young ones ($F = 15.62$, $p = 0.00$, $\eta_p^2 = 0.11$, df = 1, 122). The mean difference between young and older persons was 3.89 ± 0.41 km/h. We also observed significant main effects for Task ($F = 78.98$, $p = 0.00$, $\eta_p^2 = 0.39$, df = 1.92, 244) and for Modality ($F = 22.25$, $p = 0.00$, $\eta_p^2 = 0.39$,

TABLE 1 | ANOVA results for *mean velocity*.

Mean velocity	Condition	Group	Task	Modality	Condition × Group	Condition × Task	Condition × Modality	Group × Task	Group × Modality
F=	12.07	15.62	78.98	22.25	3.15	8.74	8.31	0.63	0.68
p=	**0.00****	**0.00****	**0.00****	**0.00****	0.08	**0.00****	**0.00****	0.53	0.41
η_p^2=	0.09	0.11	0.39	0.15	0.03	0.07	0.06	0.01	0.01
df=	1, 122	1, 122	1.92, 244	1, 122	1, 122	2, 244	1, 122	2, 121	1, 122

	Task × Modality	Condition × Group × Task	Condition × Group × Modality	Condition × Task × Modality	Group × Task × Mod.	Condition × Group × Task × Modality
F=	22.14	1.09	2.53	22.25	0.96	2.25
p=	**0.00****	0.34	0.11	**0.00****	0.38	0.11
η_p^2=	0.15	0.01	0.02	0.15	0.01	0.01
df=	2, 244	2, 121	1, 122	2, 244	2, 121	2, 121

*$p < 0.05$, **$p < 0.001$.

TABLE 2 | ANOVA results for *SD velocity*.

SD velocity	Condition	Group	Task	Modality	Condition × Group	Condition × Task	Condition × Modality	Group × Task	Group × Modality
F=	32.60	30.70	230.39	4.67	0.32	5.51	23.08	0.49	0.97
p=	**0.00****	**0.00****	**0.00****	**0.03***	0.58	**0.01***	**0.00****	0.58	0.33
η_p^2=	0.21	0.20	0.65	0.04	0.00	0.04	0.16	0.00	0.01
df=	1, 122	1, 122	1.69, 206.19	1, 122	1, 122	1.84, 244	1, 122	1.69, 121	1, 122

	Task × Modality	Condition × Group × Task	Condition × Group × Modality	Condition × Task × Modality	Group × Task × Modality	Condition × Group × Task × Modality
F=	80.79	0.86	2.57	47.96	1.29	0.11
p=	**0.00****	0.42	0.11	**0.00****	0.28	0.88
η_p^2=	0.40	0.01	0.02	0.28	0.01	0.00
df=	2, 244	1.84, 121	1, 122	1.83, 223.52	1.93, 121	1.83, 121

**p* < 0.05, ***p* < 0.001.

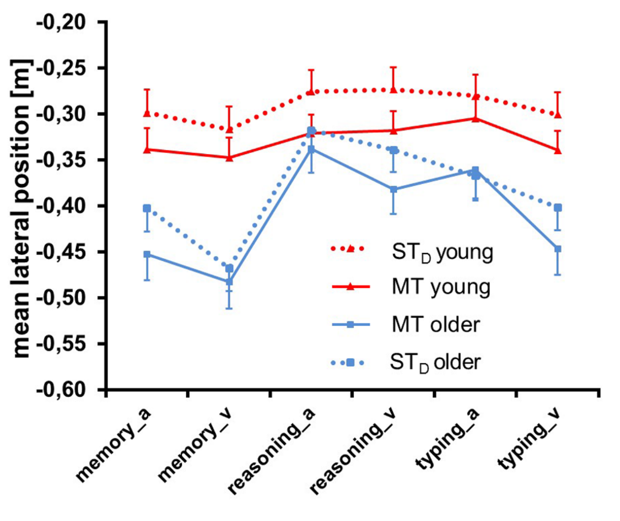

FIGURE 7 | Mean lateral position ± SE of both age groups in single task (ST_D) and multitask (MT) conditions. Memory, reasoning and typing task were presented auditorily (_a) and visually (_v).

df = 1, 122): participants drove more slowly with the reasoning compared to the memory and the typing task, and they drove more slowly when tasks were presented visually rather than auditorily.

Figure 6 illustrates corresponding data for the parameter *SD velocity*. ANOVA (see **Table 2**) revealed a significant main effect for Condition: speed variability scores were 0.75 ± 0.48 km/h higher in MT compared to ST_D ($F = 32.60$, $p = 0.00$, $\eta_p^2 = 0.21$, df = 1, 122). This increase was particularly pronounced for the visually presented reasoning task and when the typing task was presented auditorily (significance for Condition × Task, Modality, Condition × Modality, Task × Modality and Condition × Task × Modality). We further found a significant main effect for Group ($F = 30.70$, $p = 0.00$, $\eta_p^2 = 0.20$, df = 1, 122): variability scores were −1.87 ± 0.19 km/h higher in older compared to young persons. We also found a significant main effect for Task ($F = 230.39$, $p = 0.00$, $\eta_p^2 = 0.65$, df = 1.69, 206.19): variability scores were higher for the reasoning task compared to the memory and the typing task.

Figure 7 shows the parameter *mean lateral position* of both age groups in ST_D and in MT, separately for all six combinations of loading task and modality. ANOVA (see **Table 3**) yielded a significant main effect for Condition: participants drove more laterally in MT compared to ST_D ($F = 11.10$, $p = 0.00$, $\eta_p^2 = 0.08$, df = 1, 122). Mean difference between MT and ST_D was 0.12 ± 0.05 m. This shift toward the curb was larger when the memory task was presented visually and when the reasoning and typing tasks were presented auditorily, more so in older than in young persons [significance for Modality ($F = 61.91$, $p = 0.00$. $\eta_p^2 = 0.34$, df = 1, 122), Group × Modality, Task × Modality and Condition × Group × Modality]. The main effect for Group was not significant, but a significant effect of Task ($F = 79.79$, $p = 0.00$, $\eta_p^2 = 0.40$, df = 1.72, 209.82) and Group × Task emerged: participants drove more laterally when performing the memory task and this shift toward the curb was much more pronounced in older persons.

Figure 8 illustrates corresponding data for the parameter *SD lateral position*. ANOVA (see **Table 4**) revealed a significant main effect for Condition: scores were higher for MT compared to ST_D ($F = 10.53$, $p = 0.00$, $\eta_p^2 = 0.08$, df = 1, 122), but this was limited to older participants performing the typing task (significance for Task ($F = 93.68$, $p = 0.00$, $\eta_p^2 = 0.43$, df = 1.88, 244), Condition × Task, Condition × Group, Group × Task and Condition × Group × Task). Mean absolute difference between MT and ST was 0.03 ± 0.12 m. We also found a significant main effect for Group: scores were higher in older compared to young participants, with a mean difference of 0.17 ± 0.10 m ($F = 20.82$, $p = 0.00$, $\eta_p^2 = 0.15$, df = 1, 122). Finally, there was a significant main effect for Modality ($F = 53.60$, $p = 0.00$, $\eta_p^2 = 0.31$, df = 1, 122): scores were higher with auditory rather than visual

TABLE 3 | ANOVA results for *mean lateral position*.

Mean lateral position	Condition	Group	Task	Modality	Condition × Group	Condition × Task	Condition × Modality	Group × Task	Group × Modality
F=	11.10	1.36	79.79	61.91	0.27	1.85	2.36	23.24	10.93
p=	**0.00****	0.25	**0.00****	**0.00****	0.61	0.16	0.13	**0.00****	**0.00****
η_p^2=	0.08	0.01	0.40	0.34	0.00	0.02	0.02	0.16	0.08
df =	1, 122	1, 122	1.72, 209.82	1, 122	1, 122	2, 244	1, 122	1, 121	1, 122

	Task × Modality	Condition × Group × Task	Condition × Group × Modality	Condition × Task × Modality	Group × Task × Modality	Condition × Group × Task × Mod
F=	7.94	0.12	3.11	10.49	0.69	2.93
p=	**0.00****	0.88	0.08	**0.00****	0.50	0.06
η_p^2=	0.06	0.00	0.02	0.08	0.01	0.02
df=	2, 244	1.95, 121	1, 122	2, 244	2, 121	2, 121

**$p < 0.001$.

task presentation, particularly for older participants in the typing task (significance for Group × Modality, Task × Modality and Group × Task × Modality).

We noticed that participants sometimes veered off their driving lane when they engaged in the typing task. 78% of older participants but only 40% of young ones reached the curb with their right wheels during at least one presentation of the typing task; this age difference is statistically significant (test of proportions: $p < 0.001$). Furthermore, 15% of older participants but 0% of young ones crossed the median with their left wheels at least once; this age difference is again statistically significant ($p < 0.01$).

Loading Tasks

Figure 9 depicts the RT in the typing task. ANOVA (see **Table 5**) yielded a significant main effect for Condition ($F = 30.70$, $p = 0.00$, $\eta_p^2 = 0.20$, df = 1, 122): RT was higher in MT compared to the ST_L; however, this finding was limited to older participants (significance for Group × Condition). The mean difference between MT and ST_L was -0.32 ± 0.29 s. We further found a significant main effect for Group: RT of older participants was 0.37 ± 0.18 s higher than that of young ones ($F = 10.22$, $p = 0.00$, $\eta_p^2 = 0.08$, df = 1, 122). We also observed a significant main effect for Modality ($F = 124.44$, $p = 0.00$, $\eta_p^2 = 0.50$, df = 1, 122): RT was higher with auditory compared to visual presentation, more so in MT (significance for Condition × Modality) and in young persons (significance for Group × Modality).

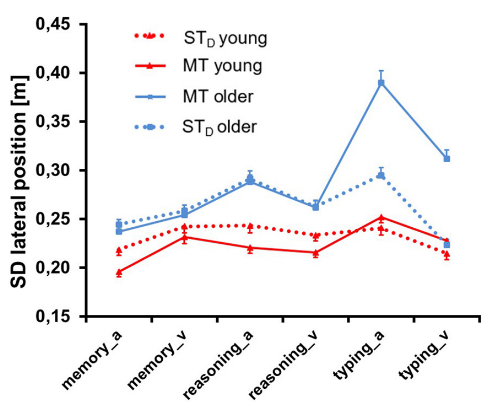

FIGURE 8 | Standard deviation of lateral position ± SE of both age groups in single task (ST_D) and multitask (MT) conditions. Memory, reasoning and typing task were presented auditorily (_a) and visually (_v).

Figure 10 shows COR in the typing task. ANOVA (see **Table 6**) revealed a significant main effect for Condition ($F = 66.00$, $p = 0.00$, $\eta_p^2 = 0.35$, df = 1, 122): COR was lower by 0.036 ± 0.007 in MT compared to ST_L, but this difference only occurred for older participants (significance for Condition × Group). There also was a significant main effect for Group ($F = 8.56$, $p = 0.00$, $\eta_p^2 = 0.07$, df = 1, 122) and for Modality ($F = 8.78$, $p = 0.00$, $\eta_p^2 = 0.07$, df = 1, 122), as COR was lower by 0.026 ± 0.012 in older compared to young persons, and lower for auditory compared to visual presentation.

Reaction time data from the memory task were not analyzed (see above), and COR data were not complete since the data sets of two older persons were lost for technical reasons. The remaining data are shown in **Figure 11**. ANOVA (see **Table 7**) revealed only a significant main effect for Group: COR was lower by 0.057 ± 0.011 in older compared to young participants ($F = 19.31$, $p = 0.00$, $\eta_p^2 = 0.14$, df = 1, 122).

DISCUSSION

This study deals with multitasking in simulated car driving. It differs from earlier work on this topic in two ways. First, we use not just one repetitive loading task but rather a mixed sequence of different loading tasks, to simulate

TABLE 4 | ANOVA results for *SD lateral position*.

SD lateral position	Condition	Group	Task	Modality	Condition × Group	Condition × Task	Condition × Modality	Group × Task	Group × Modality
F=	10.53	20.82	3.68	53.69	23.53	129.78	1.00	25.16	25.41
p=	**0.00****	**0.00****	**0.00****	**0.00****	**0.00****	**0.00****	0.32	**0.00****	**0.00****
η_p^2=	0.08	0.15	0.43	0.31	0.16	0.52	0.01	0.17	0.17
df=	1, 122	1, 122	1.88, 244	1, 122	1, 122	1.68, 204.55	1, 122	1.88, 121	1, 122

	Task × Modality	Condtion × Group × Task	Condtion × Group × Modality	Condition × Task × Modality	Group × Task × Modality	Condition × Group × Task × Mod
F=	140.66	18.48	1.50	1.02	4.45	0.44
p=	**0.00****	**0.00****	0.22	0.36	**0.01***	0.62
η_p^2=	0.54	0.13	0.01	0.01	0.04	0.00
df=	1.89, 230.33	1.68, 121	1, 122	1.82, 221.73	1.89, 121	1.82, 121

*$p < 0.05$, **$p < 0.001$.

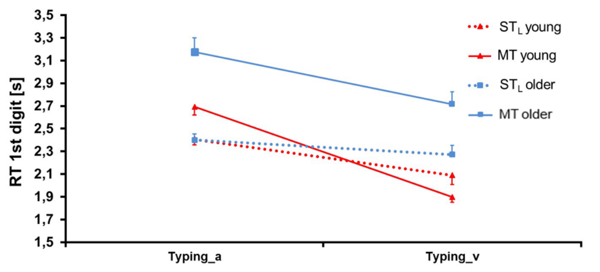

FIGURE 9 | Reaction time (RT) ± SE in the typing task for both age groups in single task (ST_D) and multitask (MT) conditions. The typing task was presented auditorily (_a) and visually (_v).

the natural interplay of dual-tasking and task switching. Second, we compare driving performance of young to that of older persons. Our work addressed three hypotheses. According to one, performance of young and older persons will decrease under multitasking conditions. Indeed, we found significant main effects of Condition for all six outcome parameters. According to our second hypothesis, the effects of multitasking will be larger with visual compared to auditory loading tasks, because of structural interference. We found significance of Condition*Modality for only three of our six parameters; we also observed three significant effects of Condition*Task*Modality, since effects of multitasking were sometimes smaller rather than larger with a visual loading task. We therefore found no unanimous support for the second hypothesis. Our third hypothesis stipulates that multitasking deficits may not be much larger in older compared to young persons, since cognitive decay is compensated by lifelong experience. Indeed, significance of Condition*Group emerged for only one driving parameter and was qualified by significance of Condition*Group*Task: when multitasking, lateral lane variability increased in older persons more than in young ones, but only with the typing task. Accordingly, significance of Condition*Group also emerged for both parameters related to typing. Our data therefore indicate that age-related deficits of multitasking emerge for some but not for other loading tasks, which adds partial support to our third hypothesis.

Compared to single-task driving, participants in MT drove at a lower speed, with a higher speed variability and at a more lateral lane position. Similarly, Chaparro et al. (2005), Horberry et al. (2006), Horrey and Wickens (2006), Strayer et al. (2006) reported lower speed and deficient lane keeping under dual- compared to single-task driving. As an example, Strayer et al. (2006) found driving speed to decrease by about 2.2 km/h when participants were talking on a mobile phone, while the decrease was about 1.4 km/h in the present multitasking study. More research is needed to find out whether our loading tasks were less disruptive than the task of Strayer et al. (2006) or, alternatively, whether multiple loading tasks

TABLE 5 | ANOVA results for *reaction time (RT)* of the typing task.

RT typing	Condition	Group	Modality	Condition × Group	Condition × Modality	Group × Modality	Condition × Group × Modality
F=	30.79	10.22	124.44	12.23	48.05	6.17	0.98
p=	**0.00****	**0.00****	**0.00****	**0.00****	**0.00****	**0.01***	0.32
η_p^2=	0.20	0.08	0.50	0.09	0.28	0.05	0.01
df=	1, 122	1, 122	1, 122	1, 122	1, 122	1, 122	1, 122

*$p < 0.05$, **$p < 0.001$.

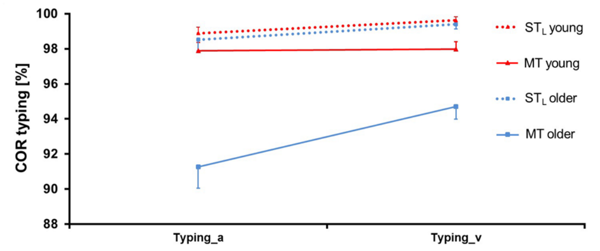

FIGURE 10 | Correctness (COR) ± SE in the typing task for both age groups in single task (ST_D) and multitask (MT) conditions. The typing task was presented auditorily (_a) and visually (_v).

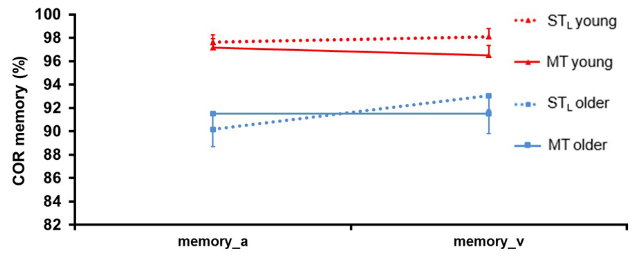

FIGURE 11 | Correctness (COR) ± SE in the memory task for both age groups in single task (ST_D) and multitask (MT) conditions. The memory task was presented auditorily (a) and visually (v).

are less disruptive than one single loading task. The observed reduction of driving speed and the more lateral lane position could represent compensatory strategies, implemented to avoid collisions with the leading car and with oncoming traffic in high-demand driving situations. The observed increase of speed variability could be a more direct marker of high demand: possibly, participants slowed down when their attention was focused on the loading task, and sped up to catch up with the leading car when attention was redirected to the driving task.

We further found that compared to young participants, older ones drove at a lower speed, with a higher speed variability and at a more lateral lane position. In other words, old age and multitasking had similar effects on driving, and possibly so for similar reasons, namely, a higher cognitive demand of driving. We also observed that older persons' performance on the memory task was poorer than that of young ones, which concurs with the known age-related deficits of working memory (Salthouse and Babcock, 1991; Waters and Caplan, 2001; Voelcker-Rehage et al., 2006).

Chaparro et al. (2005) reported that a loading task had stronger effects on driving when it was presented visually rather than auditorily. We can't confirm this observation unanimously, and therefore can't claim unequivocal support for the structural-interference model (Gopher and Donchin, 1986; Duncan et al., 1997).

Although we hypothesized that age related deficits of multitasking are compensated by experience (see section "Introduction") differential effects of age on multitasking were observed. Performance of older persons suffered more than that of young ones with the loading task 'typing,' not with 'reasoning' or 'memory.' Critically, this often let especially older persons veer off the lane when typing. The detrimental effect 'typing' on older persons could reflect the known age-related problems of attention engagement/disengagement (D'Aloisio and Klein, 1990), gaze control (Maltz and Shinar, 1999; Bock et al., 2015) and/or limb coordination (Darling et al., 1989; Ketcham et al., 2002). Since the keypad was located near the steering wheel, participants had to shift their attention, gaze and arm toward a new location in task 'type,' but not in the other two loading tasks. In any case, our finding could be of substantial relevance for the driving safety of older persons since activities similar to task 'type' are quite

TABLE 6 | ANOVA results for *correctness (COR)* of the typing task.

COR typing	Condition	Group	Modality	Condition × Group	Condition × Modality	Group × Modality	Condition × Group × Modality
F=	66.00	8.56	8.78	10.36	1.41	0.11	0.04
p=	**0.00****	**0.00****	**0.00****	**0.00****	0.24	0.74	0.83
η_p^2=	0.35	0.07	0.07	0.08	0.01	0.00	0.00
df=	1, 122	1, 122	1, 122	1, 122	1, 122	1, 122	1, 122

***p* < 0.001.

TABLE 7 | ANOVA results for *correctness (COR)* of the memory task.

COR memory	Condition	Group	Modality	Condition × Group	Condition × Modality	Group × Modality	Condition × Group × Modality
F=	0.74	19.31	0.78	0.04	2.34	0.78	0.53
p =	0.39	**0.00****	0.38	0.85	0.13	0.38	0.47
η_p^2=	0.01	0.14	0.01	0.00	0.02	0.01	0.00
df=	1, 122	1, 122	1, 122	1, 122	1, 122	1, 122	1, 122

***p* < 0.001.

common in driving: drivers often operate radios, navigation systems and other dashboard instruments, open and close windows, adjust side and rear mirrors, and on longer trips may even reach for drinks and food located elsewhere in the car cabin. It would be interesting to know whether multitasking skills can be improved by practice. Previous work has shown that dual- but not single-task training improves dual-task performance (Silsupadol et al., 2009) and accordingly, multitask- but not dual- or single-task training may improve performance on a realistic multitask.

Future research should determine whether the effects of multitasking in our study, and their modulation by age, are similar, larger or smaller than those documented by traditional dual-task studies which disregarded the natural interplay of dual-tasking and task switching (see section "Introduction"). Furthermore, our present multitasking paradigm should be expanded to allow for more than two tasks at a given time; for example, participants could drive a car, memorize events in the environments and keep up a conversation all at the same time, then switch to driving, memorizing and typing, etc.

DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

CV-R and OB contributed conception and design of the study. KW wrote the first draft of the manuscript. CV-R, CJ, MH, UD, OB, and KW wrote sections of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

FUNDING

This research was supported by a grant within the Priority Program, SPP 1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), grants BO 649/22-1 and VO 1432/19-1 and by grant of the European Social Fund and the Free State of Saxony to CJ.

ACKNOWLEDGMENTS

We wish to thank Wim Van Winsum and Thomas Kesnerus for the modification of the simulator software and constant support. We also thank Rieke Schmale, Gisli Barthelmess, Sandra Goertz, Verena Herzoff, Clara Rentz, Damaris Wallmeroth, Jacqueline Kasemir, Lorenz Baumjohann, Martin Rebro, Karim Aly, Stella Henn, Vincent Drießen, Isarn Babel, Maria Andrea Neubert, Malte Liebl-Wachsmuth, and Karolina Boxberger for their assistance in data collection and data analyses.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 13 June 2018
doi: 10.3389/fpsyg.2018.00947

Profiles of Cognitive-Motor Interference During Walking in Children: Does the Motor or the Cognitive Task Matter?

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OPEN ACCESS

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Specialty section:
This article was submitted to Movement Science and Sport Psychology,
a section of the journal Frontiers in Psychology

Received: *02 February 2018*
Accepted: *23 May 2018*
Published: *13 June 2018*

Citation:
Schott N and Klotzbier TJ (2018) Profiles of Cognitive-Motor Interference During Walking in Children: Does the Motor or the Cognitive Task Matter? Front. Psychol. 9:947.
doi: 10.3389/fpsyg.2018.00947

The evidence supporting the effects of age on the ability to coordinate a motor and a cognitive task show inconsistent results in children and adolescents, where the Dual-Task Effects (DTE) – if computed at all – range from either being lower or comparable or higher in younger children than in older children, adolescents and adults. A feasible reason for the variability in such findings is the wide range of cognitive tasks (and to some extend of motor tasks) used to study Cognitive-Motor Interference (CMI). Our study aims at determining the differences in CMI when performing cognitive tasks targeting different cognitive functions at varying walking pathways. 69 children and adolescents (boys, $n = 45$; girls, $n = 24$; mean age, 11.5 ± 1.50 years) completed higher-level executive function tasks (2-Back, Serial Subtraction, Auditory Stroop, Clock Task, TMT-B) in comparison to non-executive distracter tasks [Motor Response Task (MRT), TMT-A] to assess relative effects on gait during straight vs. repeated Change of Direction (COD) walking. DT during COD walking was assessed using the Trail-Walking-Test (TWT). The motor and cognitive DTE were calculated for each task. There were significant differences between 5th and 8th graders on single gait speed on the straight ($p = 0.016$) and the COD pathway ($p = 0.023$), but not on any of the DT conditions. The calculation of DTEs revealed that motor DTEs were lowest for the MRT and highest for the TWT in the numbers/letters condition ($p < 0.05$ for all comparisons). In contrast, there were cognitive benefits for the higher-order cognitive tasks on the straight pathways, but cognitive costs for both DT conditions on the COD pathway ($p < 0.01$ for all comparisons). Our findings demonstrate that DT changes in walking when completing a secondary task that involve higher-level cognition are attributable to more than low-level divided attention or motor response processes. These results specifically show the direct competition for higher-level executive function resources important for walking, and are in agreement with previous studies supporting the cognitive-motor link in relation to gait in children. This might be in line with the idea that younger children may not have adequate cognitive resources.

Keywords: children, locomotion, dual task, Trail-Walking-Test, visuo-spatial working memory, executive attention network, cognitive-motor interference

INTRODUCTION

Can I have your attention, please? Multitasking is already embedded in the daily lives of children and adolescents: 70% of high-school students spent half of their time in class with recreational activities and other non-academic related activities while attending lectures (Lauricella and Kay, 2010); however, studies show that using a laptop or a cell phone during class limit recall of class material (Hembrooke and Gay, 2003). Adolescents spend 60% of the time they set aside for homework switching between homework and other activities (e.g., emails, instant messaging; playing video games; navigating through their home while carrying a tray of food; Foehr, 2006). Recently, Baumgartner and Sumter (2017) showed that children aged 6–13 years find it difficult to focus their attention on a main activity in the presence of appealing media distractors, e.g., walking, crossing a street while using a mobile was found to be the primary explanation for increasing rates of pedestrian injuries (Byington and Schwebel, 2013; Thompson et al., 2013; Retting and Rothenberg, 2015). Also, most other tasks of everyday life (e.g., crossing a room while carrying an object; driving a car while making a call) or in sport settings (e.g., dribbling a ball while scanning around for a teammate to whom to pass) are not done in isolation, requiring the individual to perform two or more tasks either simultaneously or in rapid succession.

The ability to complete this type of tasks without errors requires management of attention and task prioritization so that all tasks may be completed efficiently, but attentional resources are not infinite (Pashler, 1994). Coordinating a motor and a cognitive task (dual-tasking, DT) might result in performance decrements in one or both tasks, relative to performance of each task separately. This occurs when the two tasks interfere with one another, known as cognitive-motor interference (CMI), and is thought to be a proof of capacity limitation in cognitive abilities (Watanabe and Funahashi, 2014). An increase in CMI during gait has been shown in younger and older adults with and without multiple clinical conditions such as concussion, Multiple Sclerosis, Parkinson, or dementia resulting in impaired functional gait performance and increased risk of falls (Wajda and Sosnoff, 2015; Smith et al., 2016; Belghali et al., 2017; Klotzbier and Schott, 2017; Schott, 2017; Fino et al., 2018). However, data is limited for both healthy children and adolescents.

The few studies that have examined cognitive-motor interference in typically developing children and adolescents have primarily used walking straight ahead as their motor task (Whitall, 1991; Huang et al., 2003; Cherng et al., 2007; Schaefer et al., 2010, 2015; Anderson et al., 2011; Krampe et al., 2011; Boonyong et al., 2012; Beurskens et al., 2015, 2016; Hagmann-von Arx et al., 2016; Hinton and Vallis, 2016; Chauvel et al., 2017). Walking is thought to be an automated skill in adulthood, successfully coordinated with only minimal use of attention-demanding executive control resources (Clark, 2015; Bisi and Stagni, 2016). Kraan et al. (2017) describe the changes of gait across childhood as steady and similar to adults around 7–8 years of age with changes in gait speed from 0.6 to 1.1 m/s. However, they also point out that temporal and spatial parameters will improve with subtler changes around 11–15 years. Hausdorff et al. (1999) argue that the development of the central nervous system has a greater impact on gait variability than anthropomorphic characteristics. This is even more evident, when examining complex situations such as navigating around or over obstacles (e.g., avoiding other individuals on a sidewalk or during sports events; walking through narrow openings). To maintain balance with these challenging aspects, individuals need to constantly modify their movement patterns to propel in response to environmental constraints using reactive or anticipatory strategies. This is referred to as adaptive locomotion (Higuchi, 2013). Children use different anticipatory strategies than adults, making last minute adjustments, while adults plan well ahead of upcoming obstacles. For instance, Vallis and McFadyen (2005) found in middle-aged children (9–12 years of age) reductions in gait speed and step length only two steps and one step prior to obstacle circumvention, respectively, while adults maintain a constant speed and step length. Therefore, the automaticity of the locomotor system depends also heavily on gait task difficulty (Schott et al., 2016).

In recent years, researchers focus especially on the relationship between DT performance, the attention network, and executive functions (e.g., planning, shifting, inhibition, dividing of attention) to shed light on higher-order cognitive functions (McFadyen et al., 2015; Walshe et al., 2015). Executive functions continue to develop throughout childhood with increasing efficiency at around 7 years of age (Davidson et al., 2006) well into adolescence (Pozuelos et al., 2014) and early adulthood (Anderson et al., 2011). However, the rate of this change is driven by both age and performance changes over time, e.g., a recent study demonstrated that performance in a task similar to the Wisconsin Card Sorting Task increased rapidly in childhood and early adolescence (8–14 years) after which it stabilized (Koolschijn et al., 2011). In another recent study, Boelema et al. (2014) revealed developmental trajectories for the maturation of different executive function tasks during adolescence: While inhibition reached mature levels first, information processing speed, working memory, and shift attention exhibited largest change rates and therefore most maturation between the transitions from childhood to adulthood (Schott and Klotzbier, 2018). In spite of this, evidence for the maturational timeline of executive function during childhood and adolescence is inconsistent, with findings of the rate of improvement varying considerably between individuals (Shanmugan and Satterhwaite, 2016). As Yang et al. (2017) point out, it remains unknown how these cognitive functions interact when subjects need to solve two tasks at the same time. Moreover, the refinement of cognition and DT ability results from the emergence of networks of coordinated activity spanning multiple distributed regions (Petersen and Sporns, 2015). Due to these changes one can assume that DT performance should also go through significant change during this period (Yang et al., 2017). However, to date only few studies have investigated DT in typically developing children, who exhibiting typically greater vulnerability to Dual Task Effects (DTE). The evidence supporting the effects of age on the ability to coordinate a motor and a cognitive task show inconsistent results in children and adolescents, where the DTE – if computed at all – range from either being lower or comparable or higher in younger children (4–6 years) than in older children (7–12 years), adolescents and adults (Whitall, 1991; Huang et al., 2003; Cherng et al., 2007; Schaefer et al., 2010, 2015; Anderson et al., 2011; Krampe et al., 2011; Boonyong et al., 2012; Beurskens et al., 2015, 2016; Hagmann-von Arx et al., 2016; Hinton and Vallis, 2016; Chauvel et al., 2017; see also Saxena et al., 2017 for an excellent review). For instance, Boonyong et al. (2012) found that children aged 5 and 6 years, and 7–16 years, use a more careful strategy (e.g., reduced gait speed and step length), than that of adults during obstacle crossing while performing an Auditory Stroop-Task. Hagmann-von Arx et al. (2016) reported that gait performance in children and adolescents (6.7–13.2 years), was stronger affected in a motor dual-task condition in which children were asked to fasten and unfasten a shirt button than in a cognitive dual-task condition in which children were asked to listen to and memorize digits while walking. However, no age-dependent dual-task effects on gait velocity in the cognitive dual-task condition were found. Moreover, Schaefer et al. (2010) comparing 9-year old children and adults while performing an 1- to 4-Back task during treadmill walking showed an increase in variability of spatio-temporal parameters, but improved cognitive performance under low cognitive loads. Yang et al. (2017) suggest to include not only children aged 10 years of age and less, but due to the continuous development of cognitive functions underlying DT ability (e.g., time monitoring, prospective memory, planning) children older than 10 years may provide new insights into DT development and its underlying processes during late childhood.

These findings may be interpreted from a methodological perspective and/or from the perspective of the cross-domain competition model (Lacour et al., 2008), which postulates that a motor and a cognitive task compete for attentional resources. Its main prediction is that maintaining kinematic gait parameters should be less efficient in DT than ST conditions, which in turn depends on the complexity of the selected task as well as the development of the selected cognitive domain. Recent reviews by Ruffieux et al. (2015) and Saxena et al. (2017) examining balance and walking performance under dual-task conditions discuss several methodological issues in existing studies at length. Saxena et al. (2017) suggest seven criterions to improve overall quality of studies: appropriateness of single tasks (ST), equation of tasks, calculation of DTEs, DTE for each ST, randomization of task order, practice effects, and clear instructions. Both reviews conclude, that single-task performance of the secondary task is not assessed, thus the calculation of DTEs is not permitted. Additionally, the wide range of cognitive tasks [and to some extend of motor tasks (mostly walking straight ahead; balance on two feet or one foot)] is another possible reason for the variability in findings used to study CMI with different types of cognitive and motor DT leading to different types of cognitive-motor interference (Kraan et al., 2017). To date, the cognitive tasks used in CMI studies include auditory, verbal and visuo-spatial working memory (Digit Recall; N-Back, Digit Span), inhibition (Stroop), and verbal fluency. As pointed out earlier, different components of EF have been shown to develop at different rates; therefore, the results for the relationship of motor and cognitive performance rely highly on the selected cognitive task. Most studies dealing with CMI use only one cognitive task. Researchers using different motor and multiple cognitive tasks have failed to refer to the cognitive functions targeted by the secondary tasks or did not compare the changes in CMI caused by two different tasks (Patel et al., 2014). However, different cognitive tasks may interfere with walking to a different extent, depending on the cognitive demands of the tasks (Schott et al., 2016).

The purpose of this project was to determine the differences in children's and adolescents CMI when performing cognitive tasks targeting different cognitive functions at varying walking pathways. Thus, the aims of this study were (1) to examine the effect of higher-level executive function tasks (2-Back, Serial Subtraction, Stroop- and Clock-task) in comparison to non-executive distracter tasks (motor task) on motor and cognitive costs of dual-task walking and (2) to determine the effect of straight versus Change-of-Direction (COD) -walking on motor and cognitive costs of dual-task walking.

We hypothesized that higher motor cost will be associated with a cognitive task which demands higher-level compared to lower-level executive processes, and that these costs will be higher in younger compared to older children. Higher motor and/or cognitive costs would indicate the requirement of greater attentional resources for that cognitive task, under DT conditions. We further hypothesized that compared to walking on a straight pathway COD walking while dual-tasking would decrease the performance on the cognitive tasks, i.e., increase the cognitive cost of dual-task walking.

MATERIALS AND METHODS

Participants

Sixty-nine fifth-, and eighth-graders voluntarily participated in the study (boys, $n = 45$; girls, $n = 24$; mean age, 11.5 ± 1.50 years, range 10–14 years). As mature walking patterns with upper body stability, similar to adults occur at 7–10 years of age in healthy children (Mazzà et al., 2010), we chose an age range of 10 years or older. All children and adolescents were recruited from the same mainstream school (middle socioeconomic class) in the south of Germany. They were right handed and right footed except for seven children who were left handed and left footed. None of these children had known visual, neurological or motor deficits (based on parent's report).

Local ethics committee approved the study procedures, designed in accordance with the Declaration of Helsinki on ethical standards, legal requirements and international norms. Written informed parental consent was obtained for each child and all children assented to participate.

Experimental Protocol

Each child performed both single and dual-tasks with low and high task complexity (see **Table 1**). They completed 5 single-task walking trials on a straight pathway (walking without a cognitive demand), 3 single-task walking trials on a COD pathway, 5 dual-task walking trials on a straight pathway [walking while completing (a) Auditory Stroop, (b) N-Back,

TABLE 1 | Single task (ST) and dual task (DT) conditions by task complexity (created after McIsaac et al., 2015).

Type of tasks	Task complexity	
	Low	**High**
Single motor	**Walking on a straight pathway**	**Walking on a COD pathway**
Single cognitive	• Trail-Making-Test A • Auditory Motor Task (AMT)	• Trail-Making-Test B • Auditory Stroop Task • Auditory 2-Back • Serial Subtraction Task • Clock Task
Dual motor-cognitive	• Walking on a straight pathway while responding to an auditory signal (AMT) • Walking on a COD pathway while stepping on numbered targets in a sequential order (TWT-2)	• Walking on a straight pathway while completing the (a) Auditory Stroop, (b) N-Back, (c) Serial Subtraction, and (d) Clock Task • Walking on a COD pathway while stepping on targets with increasing sequential numbers and letters (TWT-3)

TWT, Trail-Walking-Test; COD, change of direction.

(c) Serial Subtraction, (d) Clock and (e) Auditory Motor Task], and 2 dual-task walking trials on a COD pathway (walking while concurrently completing a cognitive test; TWT-2 and TWT-3). During all trials on a straight pathway, participants walked for 60 s at a self-selected pace around a 5 m × 5 m rectangle. All trials on the COD pathways (Schott, 2015) had a length of 41 m in total.

Participants were also asked to perform all cognitive tasks while seated approximately 60 cm from a 17″ blank screen laptop. They first received standardized instructions on how to perform the cognitive task. After that a familiarization procedure was carried out. E-Prime stimulus software (Psychology Software Tools, Pittsburgh, PA, United States) presented the stimuli and collected responses (accuracy, RT). Each task (single and dual) ran for 60 s in both conditions, with accuracy and/or reaction times recorded. Only the Serial Substraction Task (SST), and the Trail-Making-Test (TMT) were manually recorded.

During the dual motor-cognitive conditions, children and adolescents carried a wireless mouse in their right hand for tasks that required a button-press response. No explicit task prioritization was offered. Participants were instructed to walk as in the ST walking condition while achieving the fastest and fully accurate responses on the cognitive tasks as in the seating-only condition.

Motor task performance was either measured as the distance walked in 60 s in each walking condition (straight pathway) or as duration (COD pathway): gait speed was then calculated for each participant using distance in meters and time in seconds. It was obtained by dividing the distance traveled by the time to cover that distance. Cognitive task performance was either measured as the number of correct responses in 1 min in each condition (straight pathway) or as duration (COD pathway).

For each participant, both single-task and dual-task conditions were randomized within each condition for each participant. All single-task conditions preceded dual-task conditions to maintain consistency. To ensure that each participant understood each task they got practice trials running for 30 s. The experiment took about 90 min in total for each child.

Measures

Demographic Information, Subjective Motor Performance and Physical Activity

Basic demographic information as well as medical history were acquired by interviewing the children and their parents. Height and weight of the participants were measured, and the body mass index (BMI, kg/m^2) was calculated. Since body composition is an important independent contributor to motor and cognitive performance (Davis et al., 2015). We categorized BMI[1] according to international age- and gender-specific reference values.

The MABC-2 Checklist (Henderson et al., 2007) was created to evaluate children's motor behavior in different everyday situations of life, such as in the classroom, recreational and physical education activities and in everyday situations of personal care (Sections A, B) and in non-motor factors (Section C) that might affect movement, e.g., lack of confidence or impulsiveness. It is designed to identify children with motor difficulties in the age range 5–12 years. The Total Motor Score (TMS) is the sum of the 30-item scores (Sections A+B), the higher the TMS, the poorer the performance. The Coefficient Alpha of both groups in this study was 0.93 for all 43 items (together), 0.81 for section A (static/predictable), 0.81 for section B (dynamic/unpredictable), and 0.63 for section C (non-motor factors).

Furthermore, children were asked in which organized activities (participation through a formal club, maximum three different activities) they had participated over the past 12 months (see also Schott et al., 2016). Next, children were asked how many days a week, and minutes per session, they had participated in that particular activity. Total physical activity (h/week) was calculated as follows: (frequency 1 × duration 1) + (frequency 2 × duration 2) + (frequency 3 × duration 3). Additionally, children were asked, "Over the past 7 days, on how many days were you physically active for a total of 60 min or more per day?"

Cognitive Tasks – Straight Pathway

We adopted four cognitive tasks from Walshe et al. (2015), which are generally used to evaluate DT performance (lower-level decision-making: Auditory Motor task; higher-level executive process: Clock Task, N-Back, Serial Subtraction). Additionally, we used an Auditory Stroop Task. The duration of each task was 60 s.

The *Auditory Motor Task (AMT)* is a simple reaction time task and evaluates the processing speed of the central nervous system as well as the coordination between the sensory and the motor system. In this task, participants were presented a single auditory tone (16-Bit WAV file; 705 kbit; 1000 ms long with a 3000 ms

[1] https://nccd.cdc.gov/dnpabmi/Calculator.aspx?CalculatorType=Metric

response window from start of stimulus) at randomly varied delay intervals, (500 ms, or 1000 ms). They were instructed to quickly respond with a mouse click.

The *Clock Task* (Haggard et al., 2000) is a visuo-spatial working memory task, which requires participants to respond to an auditory speech sample announcing a time, e.g., one-twenty-five (female voice; 16-Bit WAV file; 1411 kBit; 1000 ms long with a 3000 ms response window from start of stimulus; 500 ms stimulus interval). Dividing the clock in a left and a right half participants determined whether the two hands of the clock at the given time were in the same half (left mouse click) or opposite halves (right mouse click).

An *Auditory 2-Back Task* (Owen et al., 2005) was used to assess working memory. In this study, participants heard a sequence of numbers (e.g., "3–8–3") from a female voice (Toronto Noun Pool; 16-Bit WAV file; 1536 kbit/s; 1500 ms window with randomly varied delay intervals between 2000 and 2500 ms), presented one at a time, and were required to respond with a button press (wireless mouse) to the relevant auditory numerical stimuli and to withhold responses to distractor stimuli. The stimulus sequence was different for ST and DT conditions to control for learning effects.

The *Serial Subtraction Task (SST)* measures attention, mental calculation and working memory (Karzmark, 2000). Participants were required to count backward in threes (e.g., "100–97–94") as quickly and as accurately as possible. During a practice phase, the participants counted backward from 25 in threes.

The *Auditory Stroop Task (AST)* is a modification of Stroop and is used to study cognitive control and conflict monitoring (Morgan and Brandt, 1989). The participants responded manually via wireless mouse clicks to tonality, but not to the words: they heard the words "high" and "low" spoken in either a high pitch (360 Hz) or a low pitch (180 Hz) voice. The participants were instructed to indicate the pitch of the word they heard (ignoring the actual word presented) by responding "high" (left click) or "low" (right click) as accurately and as quickly as possible.

Cognitive Tasks – COD – Pathway

The *Trail-Making-Test* (TMT, Reitan, 1955) was used to examine executive function under fine motor control conditions. Originally, the paper-and-pencil test consists of two parts: During Part A (TMT-A; attention, visual scanning, motor speed and coordination), subjects are instructed to connect encircled numbers (1–25) randomly distributed on a white sheet of paper. In Part B (TMT-B; mental flexibility and working memory in addition to the abilities assessed by part A), participants are asked to connect randomly positioned numbers (1–13) and letters (A–L) in an ascending number-letter sequence (1–A–2–B– etc.). Additionally, we included a motor speed condition (TMT motor speed) as the ST condition: participants trace over a dotted line connecting circles on the page (trail of the same length compared to TMT A and B), in order to test their ability to adapt movement accuracy to spatial constraints based on incoming visual feedback with temporal pressure (Klotzbier and Schott, 2017). During performance, errors were immediately corrected by the examiner instructing the participant to go back to the last correct item, thus increasing the time taken to complete the test. The trials were timed using a stopwatch to the nearest 0.01 s; also, the number of errors was recorded. Due to the longer total trail length of TMT B compared to TMT A (Gaudino et al., 1995) and TMT motor speed we report the speed (cm/s) instead of the total duration.

The *Trail-Walking-Test* (TWT, Schott, 2015) was used to examine executive function under gross motor control conditions. Cones with flags are placed randomly at each of 15 positions in a 16-m^2 area (4 × 4 m). 30-cm diameter circles were drawn around each cone. The participants were required to (1) follow a line of connecting circles (TWT-1, ST), (2) step on numbered targets in a sequential order (i.e., 1–2–3; TWT-2, DT), and (3) step on targets with increasing sequential numbers and letters (i.e., 1–A–2–B–3–C; TWT-3; DT). In addition, participants were instructed to move from one flag to the next in an ascending order as quickly, but as accurately as possible. However, no priority was given to one domain or the other. Trials were considered successful when the participant did not knock over a cone, step on the circle (motor errors), and did not walk in the wrong direction (sequencing and shifting errors; Klusman et al., 1989) or exhibit extended search patterns. During performance, sequencing and shifting errors were immediately corrected by the examiner instructing the participant to go back to the last correct item; motor errors were only recorded. The trials were timed using a stopwatch to the nearest 0.01 s following a standard procedure. Gait speed was calculated for each participant using distance in meters and time in seconds. It was obtained by dividing the distance traveled 41 m by the time to cover that distance. Each condition was performed three times.

Data Analysis

Statistical analyses were implemented on SPSS v.24 (SPSS, Chicago, IL, United States). We first explored dependent variables to examine missing data points, normality of distributions (tested by Kolmogorov–Smirnov tests), and presence of outliers (defined by the Explore command of SPSS v.24). An alpha level of 0.05 was used for all statistical tests. Potential baseline group differences for continuous variables (i.e., age, height, weight, BMI, physical activity, VO_2max) were assessed using ANOVAs, and categorical demographic variables (i.e., gender, weight category) were compared by chi-square test.

For measuring the performance level in the cognitive task, the computation of the "correct cognitive response" (CCR) was adopted from MacLean et al. (2017). The CCR score in the ST conditions was calculated by dividing the number of correct responses by the time taken (60 s) to produce a response rate per second. This result was then multiplied by the ratio of correct responses to total responses, to take error into account, with higher CCR scores indicating better cognitive performance. The CCR scores in the DT conditions were first calculated as the number of correct responses given in the DT, divided by the time taken for each individual DT condition and this result was then multiplied by the ratio of correct responses to total responses, to adjust for errors.

To quantify the effect of dual tasking on both motor and cognitive parameters we compared the absolute values for all cognitive and motor parameters between single- and DT-conditions. To compare the motor and cognitive function across the different DT conditions, the motor and cognitive DTEs calculated according to the common formula (Plummer and Eskes, 2015):

$$\text{DTE}\,(\%) = \frac{(\text{Dual task} - \text{Single task})}{\text{Single task time}} * 100 \quad (1)$$

Negative DTE values indicate that performance deteriorated in the DT relative to the ST (i.e., DT cost), whereas positive DTE values indicate a relative improvement in performance in the dual-task (i.e., DT benefit) (Plummer and Eskes, 2015, p. 3). It is important to examine change in both activities, because motor performance can decline in one or both of the activities performed simultaneously when they exceed the available attentional resources; thus, we examined motor and cognitive DTEs.

Correlation analysis between motor and cognitive performance and age, sex, exercise, subjective motor performance, and Vo_2max was performed using Pearson's correlation (*r*) or Spearman's rank correlation (*rSp*) in cases of not normally distributed variables. In a regression analysis, we included most relevant confounders ($|r/rSp| > 0.2$) that may interact with DT gait performance. Due to the high number of regressions performed, the level of significance was set to $p < 0.01$ to reduce the probability of alpha error accumulation.

To analyze the effect of the different task conditions on gait speed, each variable was analyzed using a 2 × 6(3) (six different conditions on the straight pathway; three different conditions on the COD pathway) repeated measure analysis of variance (ANOVA) with task conditions as the within-group factor and age group as between factors. Paired *t*-tests were performed between cognitive performance scores in the sitting and walking conditions for each cognitive task. The motor and cognitive costs across the 5 (straight pathway)/2(COD pathway) DT conditions were compared using a 2 × 5(2) repeated measures ANOVA. Significant findings were followed up with *post hoc* analysis to determine the effect of specific cognitive tasks on gait speed (motor function).

Effect size for all ANOVAs was reported using partial eta squared (η_p^2), with a small effect defined as 0.01, a medium effect as 0.06, and a large effect as 0.14 (Cohen, 1988). Repeated measures sphericity issues were addressed with the Greenhouse Geisser correction. When ANOVAs were statistically significant, *post hoc* comparisons were performed using the Bonferroni correction. The level of significance for *post hoc* comparisons was set at 0.05.

RESULTS

Participants

Table 2 depicts the demographic, subjective motor performance, physical activity, and general cognitive performance measures. Group comparisons showed that children (29 boys, 13 girls) and adolescents (16 boys, 11 girls) differed on exercise duration, subjective motor performance (TMS; total motor score of the MABC-2 Checklist A and B), and Vo_2max with adolescents outperforming children. Furthermore, girls (46.2 ± 3.59) exhibited lower Vo_2max scores compared to boys (52.0 ± 4.08), $t(67) = -5.85$, $p < 0.001$, $d = 1.07$.

Influence of Age, Sex, Exercise, Subjective Motor Performance, and Vo_2max on Motor and Cognitive Performance

Supplementary Table S1 shows univariate correlations between dependent and independent variables. Overall, we found only small to moderate correlations between age, sex, BMI, physical activity, subjective motor performance, Vo_2max and the different dual tasks (DT). The results of regression analysis for motor and cognitive performance, motor and cognitive DTEs are summarized in Supplementary Table S2. Only age showed a significant relationship to DT performance in almost all tasks on the straight pathway.

Group Differences on Gait Speed and Cognitive Performance in ST- and DT-Conditions

Gait Performance

There were significant differences between 5th and 8th graders on single gait speed on the straight pathway and the COD pathway, but not on any of the DT conditions (see **Figure 1** and Supplementary Table S3). Lower- and higher-level cognitive tasks had a significant effect on gait speed with a significantly lower gait speed during all dual-task conditions compared to the single-task walking on a straight pathway, [$F(4.2,276) = 40.4$, $p < 0.001$, $\eta_p^2 = 0.376$] as well as on the COD-pathways [$F(1.8,122) = 343$, $p < 0.001$, $\eta_p^2 = 0.836$]. However, there were no significant differences in gait speed between the Clock Task, 2-Back, SST, and Stroop, but significant differences between the TWT-1, TWT-2, and the TWT-3 condition ($p < 0.001$). Higher task complexity resulted in a higher magnitude of decline in gait speed.

Cognitive Performance

A significant main effect for condition (CCR-rate) was found, [$F(1.76,108) = 187$, $p < 0.001$, $\eta_p^2 = 0.754$] indicating better performance on the Auditory Motor Task and the Serial Subtraction Task compared to the Auditory Stroop Task, 2-Back Task, and the Clock Task. *Post hoc* tests conform that all cognitive tasks differ significantly from each other. Furthermore, the interaction for ST vs. DT by grade [$F(1,61) = 3.79$, $p = 0.056$, $\eta_p^2 = 0.058$] approached significance as well as the interaction between condition and ST vs. DT, [$F(2.11,129) = 2.55$, $p = 0.079$, $\eta_p^2 = 0.040$]. Overall, children (5th graders) performed better in the DT conditions compared to the ST conditions (CCR: 0.139 vs. 0.130), while the adolescents (8th graders) performed better in the ST conditions compared to the DT conditions (CCR: 0.146 vs. 0.136). The CCR was decreased under DT conditions only for the Auditory Motor Task, the 2-Back Task, and the Clock Task, but increased for the Serial Subtraction Task and the Auditory Stroop Task (see **Figure 2**).

TABLE 2 | Demographics, exercise, motor performance, and physical fitness of children by grade (means ± standard deviation).

	5th grade (n = 42)	8th grade (n = 27)	Statistical analysis – *p*-value
Age (years)	10.3 ± 0.53	13.2 ± 0.24	$t(67) = -24.0$, $p < 0.001$, $d = 0.70$
Sex (boys/girls)	29/13	16/11	$CHI^2(1) = 0.69$, $p = 0.405$
BMI (kg/m²)	16.4 ± 1.90	18.8 ± 1.34	$t(59) = -5.59$, $p < 0.001$, $d = 0.25$
Exercise (min/wk)	177 ± 94.6	290 ± 165	$t(77) = -3.22$, $p = 0.003$, $d = 0.17$
MABC-2 checklist			
A and B (0–90)	4.95 ± 6.25	2.26 ± 3.21	$t(64) = 2.35$, $p = 0.022$, $d = 0.54$
C (0–13)	2.17 ± 2.19	1.56 ± 2.21	$t(67) = 1.13$, $p = 0.263$, $d = 0.28$
PACER (laps)	42.5 ± 14.4	63.1 ± 19.6	$t(67) = -5.02$, $p < 0.001$, $d = 1.20$
Vo_2max	49.2 ± 5.10	51.3 ± 4.00	$t(67) = -1.83$, $p = 0.071$, $d = 0.06$

BMI, Body-Mass-Index; MABC-2 Movement Assessment Battery.

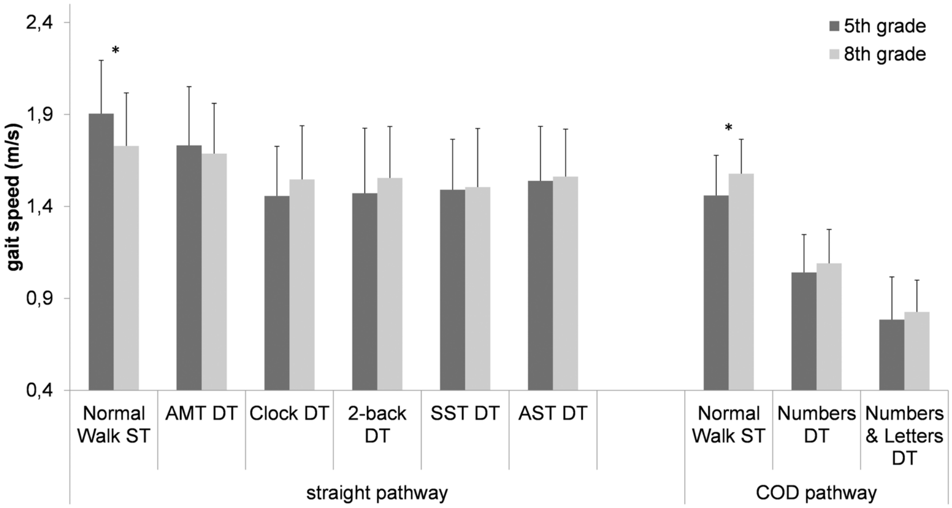

FIGURE 1 | Gait speed (means ± standard deviation) on a straight and a COD pathway as a function of type of cognitive task and age group (5th grade, 8th grade). * age groups significantly different from each other (ST, single task; DT, dual task; AMT, Auditory Motor Task; SST, Serial Subtraction Task; AST, Auditory Stroop Task).

ANOVAs with repeated measures indicated that there were significant differences between all three conditions for the Trail-Making-Test [$F(1.35,90.2) = 223$, $p < 0.001$, $\eta_p^2 = 0.769$] as well as the Trail-Walking-Test [$F(1.82,122) = 343$, $p < 0.001$, $\eta_p^2 = 0.836$] with lower speeds for the tasks with higher task difficulty (see also Supplementary Table S3). There were no significant interactions for age group × task.

Motor and Cognitive Dual Task Effects

A comparison of motor DTEs for the straight pathway revealed that motor cost was significantly lower in the simple motor response condition compared to all other conditions [$F(3.32,222) = 20.3$, $p < 0.001$, $\eta_p^2 = 0.233$] ($p < 0.05$ for all comparisons). There were no significant differences in motor costs between the Clock Task, 2-Back, SST, and Stroop (**Figure 3** left side). Motor costs for the COD- pathway in the number + letters condition were significantly higher than in the numbers condition [$F(1,65) = 79.9$, $p < 0.001$, $\eta_p^2 = 0.551$] (**Figure 3** right side). *Post hoc* comparisons showed significantly lower motor dual task costs on all tasks on the straight pathway, but not the COD pathway for adolescents compared to children ($p < 0.05$ for all comparisons).

There were also significant differences in the cognitive DTEs across tasks on the straight pathway [$F(1.94,69.9) = 4.12$, $p = 0.021$, $\eta_p^2 = 0.103$] as well as on the COD pathway [$F(1,65) = 19.8$, $p < 0.001$, $\eta_p^2 = 0.245$]. The cognitive cost of DT walking was greatest in the TWT-2 condition compared to all other conditions ($p < 0.01$ for all comparisons), whereas the cognitive cost was lowest in the motor task. *Post hoc* comparisons indicated significant better performances in the Clock Task, the Auditory 2-Back Task, and the Auditory Stroop Task for children, but significantly poorer performance for adolescents in the Auditory 2-Back Task, and the Auditory Stroop Task.

Individual comparisons of ST and DT conditions showed clear evidence of mutual interference, where motor and cognitive performance declined both under DT conditions, or prioritizing cognitive performance, such that gait speed decreased but cognitive performance improved under DT conditions (see **Figures 4A–G**).

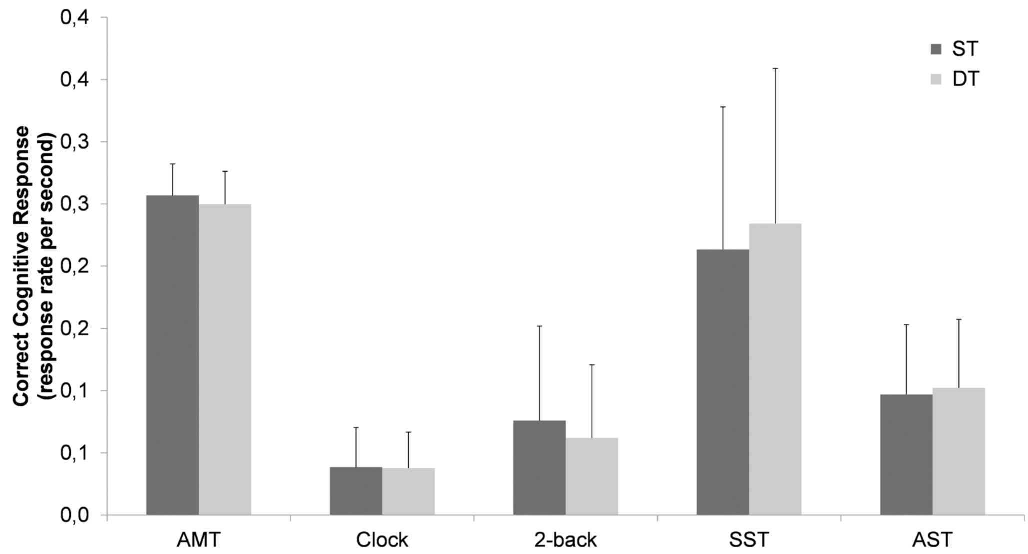

FIGURE 2 | Cognitive performance (Correct Cognitive Response, CCR) (means ± standard deviation) by walking condition (ST, single task; DT, dual task; AMT, Auditory Motor Task; SST, Serial Subtraction Task; AST, Auditory Stroop Task).

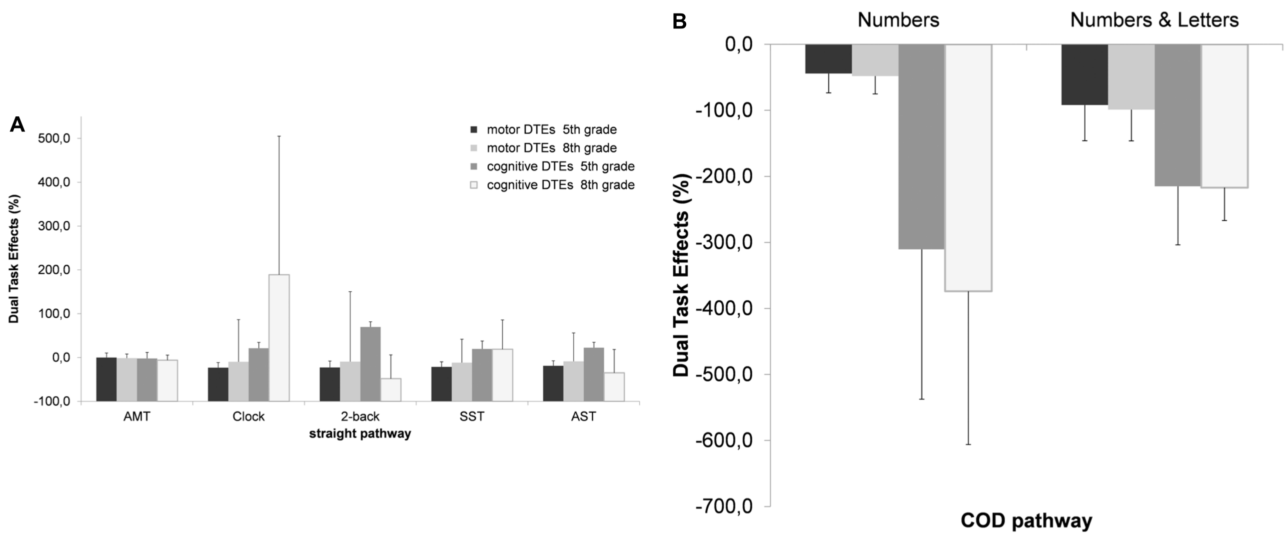

FIGURE 3 | Motor and cognitive DTEs (%, means ± standard deviation) on **(A)** a straight and **(B)** a COD pathway as a function of type of cognitive task and age group (5th grade, 8th grade) (%) (DTE, dual task effects; AMT, Auditory Motor Task; SST, Serial Subtraction Task; AST, Auditory Stroop Task) (standard deviations can be found in the Supplementary Material).

DISCUSSION

To our knowledge, this is the first study to compare the effects of different types of motor (i.e., straight vs. COD pathway) and cognitive tasks (i.e., non-executive distractor tasks vs. higher-level executive function tasks) on DT performance in children and adolescents. As expected, the main findings indicate that walking on a COD pathway is more difficult than walking on a straight pathway. Cognitive performance differed significantly in the different types of tasks, reflected in better performance for the Auditory Motor Task and the Serial Subtraction Task, followed by the Auditory Stroop Task, the 2-back Task, and the Clock Task (CCR scores), regardless of the ST vs. DT condition. Furthermore, our results show that the Auditory Motor Task was the least demanding task; higher-level executive function tasks were more demanding than non-executive distractor tasks, as reflected in non-significant differences in gait speed for these tasks on a straight pathway and the COD pathway. The calculation of DTEs revealed that motor DTEs were lowest for the Auditory Motor Task and highest for the Trail-Walking-Test in the numbers + letters condition. In contrast, there were cognitive benefits for the higher-order cognitive tasks on the

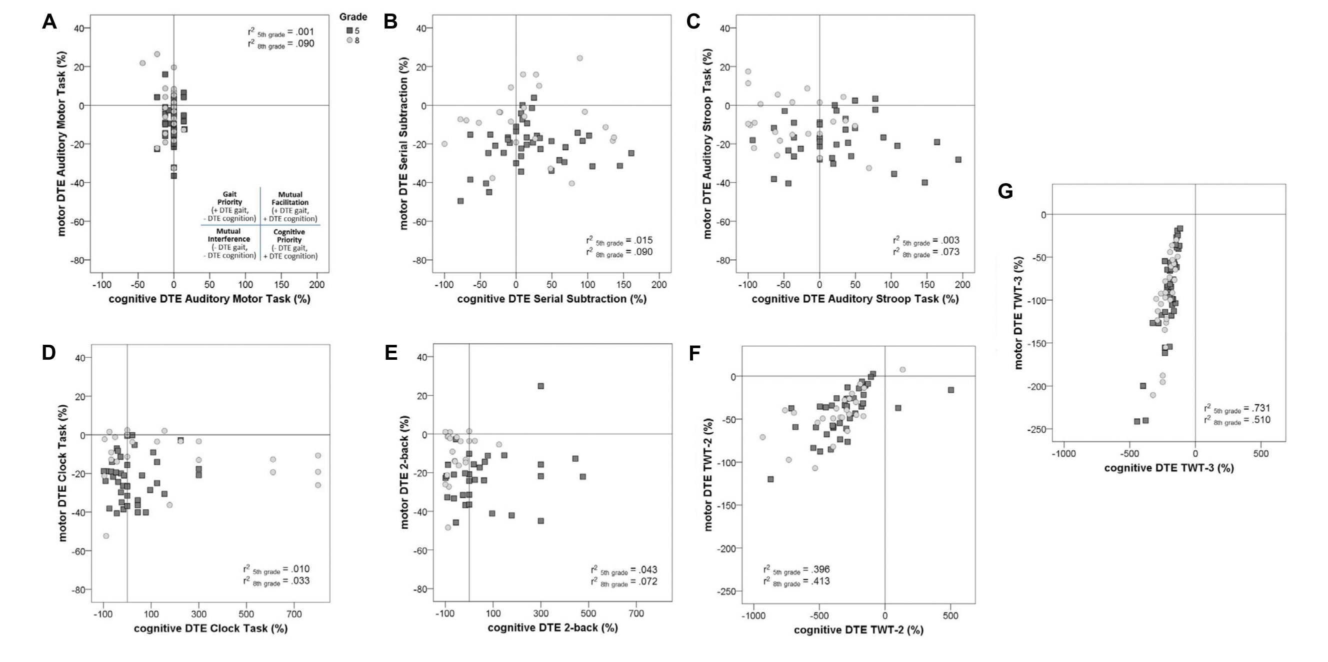

FIGURE 4 | Profiles of cognitive-motor interference across motor and cognitive tasks. DTE refers to dual task effect. Positive values for dual-task effects (DTE) indicate that performance improved in dual-task condition relative to single-task performance; negative values for DTE indicate that performance deteriorated in dual-task condition relative to single-task performance (Plummer and Eskes, 2015). **(A)** Auditory Motor Task; **(B)** Serial Subtraction Task; **(C)** Auditory Stroop Task; **(D)** Clock Task; **(E)** 2-back; **(F)** Trail-Walking-Test – numbers; **(G)** Trail-Walking-Test – numbers and letters.

straight pathways, but cognitive costs for both DT conditions on the COD pathway.

Effect of Different Motor Tasks on Cognitive-Motor Interference

The comparison of different walking tasks and their demands for dual-task walking attracted only little attention so far (Beurskens and Bock, 2013). Only few studies have examined the influence of different physical environments while dual-tasking, either using different terrains or obstacles (Schrager et al., 2008; Beurskens and Bock, 2013; Simoni et al., 2013; Lin and Lin, 2016). However, coping with everyday tasks does not just require walking on straight stretches. The treadmill or straight-walking DTs commonly used in clinical trials and in the DT research literature seem to be too simple in their demand for motor control (due to constant walking speeds and unexpected perturbations) to produce significant interferences (Schott, 2015).

While straightforward walking we observed higher gait speeds in children compared to adolescents. Only when cornering in the COD walking condition, we see an advantage in adolescents, probably due to the aforementioned requirements of the walking tasks. This suggests that cornering in children is not automated to the extent as it is in adolescents. In addition to the assumption of higher motor requirements in children, it is also conceivable that children have greater difficulty to follow the instructions. Subjects should walk at a normal walking pace without racing. During the study it could be observed that some children have tried to walk faster than instructed because they probably interpret it as a competition (lack of inhibitory control, Boelema et al., 2014).

Compared to walking straight ahead, different cognitive functions are addressed when walking on COD pathways. While straightforward walking can be solved by simple information processing, cognitive flexibility and the ability to change tasks explains the speed of cornering (Lowry et al., 2012) and walking with directional changes (Mazaheri et al., 2014). Studies also demonstrate that dual-task-related declines in gait performance are more pronounced during walking tasks requiring greater visual processing and feedforward visual planning, such as obstacle avoidance (Beurskens and Bock, 2013). Precise placement of the feet, especially in difficult environmental conditions to prevent tripping and slipping, is essential (Alexander et al., 2005), primarily visually controlled and requires some level of close attention (Menant et al., 2014). The Trail-Walking-Test follows a COD course characterized by a necessary asymmetry of foot placement and involves steering the body in different directions. Navigation in this task is a rather complex ecological activity involving spatial cognition through body motion using either an egocentric or allocentric frame of reference (Schott et al., 2016). Large-scale spatial tasks can be used to assess either egocentric spatial memory processes, but allocentric memory processes preferentially (Lavenex et al., 2015). Due to their developing executive function (Bullens et al., 2010) children as young as 10 years still exhibit incomplete spatial abilities. They are not fully able to switch between and/or simultaneously use different sources of spatial information and reference frames as it is accomplished, by fully developed adolescents (Belmonti et al., 2013; Broadbent et al., 2014). From this point of view, our results are in agreement with the literature, showing better navigational skills in older than younger children.

Considering the first aim of the study, we hypothesized that compared to straight walking COD walking while dual-tasking participants would exhibit a decrease in performance on the cognitive task. Consistent with our hypothesis, and similar to the results of Schaefer et al. (2010), we see an overall improvement in cognitive performance under DT walking on a straight pathway. In contrast, in the COD walking condition, we observed a considerable decrease in cognitive performance, primarily in the condition with low cognitive load. As the difficulty level of the secondary cognitive task in the COD walking condition increases (numbers + letters), we observe decreased cognitive costs and increased motor costs compared to the lower demanding cognitive task (numbers). Moreover, in the cognitive DT conditions no age-dependent dual-task effects were found on gait velocity regardless of the walking condition.

The beneficial effect on cognitive performance may be explained by general increases in arousal induced by the walking task (e.g., Adam et al., 1997). However, this cannot explain the cognitive decline in the COD condition. Other explanatory theoretical models have been proposed to explain conflicting findings in the locomotion-cognition literature: the Cross-Domain Competition Model (limited attentional and processing capacity in humans; Lacour et al., 2008), the U-shaped non-linear interaction model (cognitive demand of the secondary task can either improve or diminish postural stability; Huxhold et al., 2006), the Task Prioritization Model (subjects always prioritize the gait task over the cognitive activity under specific threatening conditions, known as "posture first" strategy; Shumway-Cook et al., 1997; Yogev-Seligmann et al., 2012), and Constrained Action Hypothesis (external focus facilitates of motor performance due to promoting automatic control of movement; McNevin et al., 2003).

The Cross-Domain Competition Model and the Task Prioritization Model best explain the findings of the present study. However, the "Cross Domain Competition Model" (Lacour et al., 2008) tries to explain that even two tasks that are not identical in their structure can interfere with each other. In particular, the model assumes that balance control and various cognitive tasks (primarily executive functions) compete with each other for identical brain resources, and that EF and the integration of sensory information into locomotion are important issues (Yogev-Seligmann et al., 2008), which might lead to a decline in both tasks simultaneously or in either the motor or the cognitive task performance under DT conditions. In this regard, there are findings demonstrating overlapping neural networks for postural control and visual-spatial tasks (Barra et al., 2006; Sturnieks et al., 2008) and show that visually demanding tasks or mental tracking tasks are particularly sensitive to the production of dual task costs (Al-Yahya et al., 2011; Beurskens and Bock, 2012). In light of the "Cross Domain Competition Model," the interferences in our study are explained as follows: even simple motor tasks (walking), which are primarily run by subcortical structures are characterized by non-automated processes and take up minimal attentional resources (Koenraadt et al., 2014). However, the required resources in the straight walking condition are low, so there is negligible loss of performance in the motor domain. Under more challenging motor conditions (e.g., avoiding obstacles or COD walking), postural tasks take more cognitive effort. This in turn leads to increased interference in the motor and particular in the cognitive domain. However, when there is a competition for resources, subjects might exhibit an unconscious strategy to prioritize the motor or cognitive task altering the overall motor or cognitive performance.

The "Integrated Model of Task Prioritization" (Yogev-Seligmann et al., 2012) tries to explain why there are different self-selected strategies to handle DT situations and why resource allocation or prioritization varies. The interplay between postural reserve and hazard estimation is crucial and determines which strategy of prioritization will be executed. Recent studies have found that during DT walking healthy young individuals tend to allocate most of their attention to the secondary task unless they perceive high demands from the walking task or are experts in the secondary cognitive task (Plummer and Eskes, 2015). In the current study many younger children prioritized the cognitive task during the walking task with low demands, but not during the motor task with high demands. Children with high postural reserve and hazard estimation are able to prioritize the cognitive task for an extended period without any adverse effects on gait. Thus, unlike older people, we see a "posture-second" strategy during low demanding walking conditions especially with a combination of higher-level EF tasks. When the environment becomes more complex and walking is challenged, the focus of attention shifts toward the motor task to maintain gait stability. These results are consistent with Boonyong et al. (2012) who demonstrated that children (5–6 years, and 7–16 years), apply a more careful strategy with reduced gait speed and step length during obstacle crossing while dual tasking. Schaefer et al. (2008) suggest that children invest more resources into the balance task to avoid putting their balance at risk when overall attentional demand increase. Even if a performance deterioration in the motor task and the associated possible consequences such as falls, do not have the same ecological relevance in children as in the elderly (Li et al., 2005), this tendency shows that also young children are able to exhibit healthy risk judgment (Yogev-Seligmann et al., 2012).

Effect of Different Cognitive Tasks on Cognitive-Motor Interference

As already highlighted before, studies in the field of motor-cognitive DTs exhibit an enormous variation in the use of cognitive tasks. However, different components of EF have shown to develop at different rates throughout childhood (Boelema et al., 2014). Therefore, the results for the relationship of motor and cognitive performance rely highly on the selected cognitive task. Similar to the study results of Walshe et al. (2015), we see that the task with low task complexity like the Auditory Motor Task appears to be easier to accomplish, and tasks that require higher-level EF like the Auditory Stroop Task appear to be significantly more difficult. Also in our study the Clock Task seems to have the strongest effect and seems to be the most demanding task. Walshe et al. (2015) suggest that this could be due to a doubling of executive components (both working memory and visuo-spatial imagining of the clock face) and could thus further tax the EF processing capacities.

With a closer look on the absolute times in the DT conditions, we can observe differences between the different cognitive tasks in the straight pathway walking condition. In both age groups the simple Auditory Motor Task did not increase the walking performance and thus stands in contradiction to the "U-Shaped Non-linear Interaction Model" (Lacour et al., 2008) and contrary to the hypothesis of constrained action (Wulf et al., 2001). This model states that an easy cognitive task can lead to an external focus of attention. An external focus on a highly automatic skill – such as walking – can improve the automatic control processes and enables a self-organized postural control system to facilitate walking. An internal focus of attention, on the other hand, which we could expect in the ST, disrupts the automatic control processes and could impair walking performance. However, as we do not see any improvement with the Auditory Motor Task, our results contradict to this model. In regard of the DT effects, this study demonstrates that, when completing a secondary task that taxes higher-level cognition, DT changes in gait are attributable to more than low-level motor response processes. These effects specifically show the direct competition for higher-level EF resources while walking and are in agreement with previous studies supporting the EF-motor link in relation to gait (Mirelman et al., 2012). Unlike Walshe et al. (2015), however, in children or adolescents we see no clear difference in dual task costs between these different higher-level EF tasks in the walking straight condition. Indeed, in the more challenging COD walking condition we observe that gait speed decreases with increasing task difficulty. It seems that the most cognitive challenging dual-task paradigms for children are those in which visual scanning of the external environment is required (Matthis et al., 2017). In this respect, in addition to visual scanning also cognitive processing speed, linguistic, executive and attention components are recorded with the TWT (Schott, 2015). However, since this is a mobile version of the TMT (Reitan, 1955) and the TMT primarily allows a statement about cognitive flexibility (Crowe, 1998) and is probably the most widely used tool for assessing the ability to change tasks (Arbuthnott and Frank, 2000), there seems to be a strong correlation between the construct of cognitive flexibility and complex locomotion tasks. Ble et al. (2005), Hirota et al. (2008) as well as Killane et al. (2014) were able show that individuals with poor performance in cognitive flexibility have difficulty controlling their gait and adapting it to increased motor demands. The aforementioned connection between the construct of cognitive flexibility and locomotion manifests itself inter alia in the fact that the prefrontal cortex is active both, in the processing of the TMT and in locomotor tasks (La Fougere et al., 2010; Lee et al., 2014). This indicates the sharing and common use of the prefrontal cortex and associated neuronal areas when performing the TWT and explains why we observe the most interference in this study.

Study Limitations and Future Directions

The results of this study suggest that cognitive and motor DT gait evaluation may be incorporated into the evaluation of executive functions. However, some limitations to this study should be noted. This study's limitations mainly encompass the cross-sectional design. Due to this design, a causal relationship between maturation and the observed findings regarding walking measured under single and dual-task conditions cannot be drawn. Longitudinal studies are needed to detect the factors, such as physical and cognitive improvements, that may more directly contribute to attentional demands exceeding total capacity in dual-task performance across childhood. In addition, measures such as the Tanner stage, hormonal assays, or a combination of techniques should be used, when examining DT performance in participants in the puberty stage (Dorn et al., 2006).

Furthermore, the quantification of children's gait performance was characterized by only a single quantitative parameter (duration), but not qualitative parameters. As different variables (duration and distance) are used, the comparison of conditions is only possible to a limited extent. When interpreting the results and differences in straight walking or COD walking this must be taken into account. Although duration is a typical measurement in DT literature, other studies have shown that spatiotemporal patterns are differentially related to dual-task performance (Kraan et al., 2017). Therefore, future studies should include metrics that quantify parameters such as step- and stride length, double support time, head and body movements. However, using a more complex walking route rather than walking on a straight pathway increased the ecological validity of our walking task. The aim is to generate as realistic as possible situations through the respective test procedure. Moreover, no instructions were given to subjects regarding task prioritization: however, young children are able to exhibit healthy risk judgment (Yogev-Seligmann et al., 2012). They allocate most of their attention to the motor task when they perceive high demands from the walking task. It would be interesting to see if this is true even for older adults. This is crucial in order to make a statement regarding resource allocation strategies in the elderly and to assess their risk of falling (Schott and Klotzbier, unpublished). It also seems important to mention that it cannot be said with absolute certainty that the difficulty of the motor tasks with the frequent changes of direction (COD) in the TWT is responsible for the increased costs. It could well be that only the visual claim is decisive. We did not have any visually demanding requirements in any straightforward dual task condition. Future studies should consider different levels of difficulty in locomotion tasks with visually challenging additional cognitive tasks to better understand the relative demands for attention.

Another limitation was that conditions were not counterbalanced for ST and DT and therefore, results can only be interpreted in the context of STs occurring first and DTs occurring after all STs had been performed. Despite this, children and adolescents were faster in the ST conditions, and their performance deteriorated with increased task difficulty in the DT conditions. Thus, if anything, counterbalancing may have increased the magnitude of the observed differences.

Last but not least a better understanding of the neural mechanisms of DT effects as well as the involvement of EF in DT performance might help to use DT training in clinical populations (Leone et al., 2017).

CONCLUSION

Our findings demonstrate that when completing a secondary task that involve higher-level cognition, DT changes in walking (straight as well as COD-pathways) are more pronounced than low-level divided attention or motor response processes. These results specifically show the direct competition for higher-level EF resources important for walking, and are in agreement with previous studies supporting the EF-motor link in relation to gait in children as well as older adults (Walshe et al., 2015; Saxena et al., 2017). This observation is particularly notable in complex locomotion tasks as our study shows and is in line with the idea that younger children may not have adequate cognitive resources. Walshe et al. (2015, p. 9) claim that an "underlying executive control system operates as an orchestrating body, allocating resources to and integrating information from the sensory inputs necessary for complex real-world walking." In future studies, consideration should increasingly be given to more ecologically valid locomotion tasks in order to investigate motor-cognitive interferences in children.

AUTHOR CONTRIBUTIONS

NS and TK contributed to writing, data analysis, and results. TK contributed to data collection and wrote the computer program for the cognitive tasks.

ACKNOWLEDGMENTS

We thank Pia Bönisch as well as Jasmin Fischer for their support in data collection.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.00947/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 06 June 2018
doi: 10.3389/fpsyg.2018.00912

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Single- and Dual-Task Balance Training Are Equally Effective in Youth

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OPEN ACCESS

Edited by:
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University of Augsburg, Germany

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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *24 January 2018*
Accepted: *18 May 2018*
Published: *06 June 2018*

Citation:
Lüder B, Kiss R and Granacher U (2018) Single- and Dual-Task Balance Training Are Equally Effective in Youth. Front. Psychol. 9:912. doi: 10.3389/fpsyg.2018.00912

Due to maturation of the postural control system and secular declines in motor performance, adolescents experience deficits in postural control during standing and walking while concurrently performing cognitive interference tasks. Thus, adequately designed balance training programs may help to counteract these deficits. While the general effectiveness of youth balance training is well-documented, there is hardly any information available on the specific effects of single-task (ST) versus dual-task (DT) balance training. Therefore, the objectives of this study were (i) to examine static/dynamic balance performance under ST and DT conditions in adolescents and (ii) to study the effects of ST versus DT balance training on static/dynamic balance under ST and DT conditions in adolescents. Twenty-eight healthy girls and boys aged 12–13 years were randomly assigned to either 8 weeks of ST or DT balance training. Before and after training, postural sway and spatio-temporal gait parameters were registered under ST (standing/walking only) and DT conditions (standing/walking while concurrently performing an arithmetic task). At baseline, significantly slower gait speed ($p < 0.001$, $d = 5.1$), shorter stride length ($p < 0.001$, $d = 4.8$), and longer stride time ($p < 0.001$, $d = 3.8$) were found for DT compared to ST walking but not standing. Training resulted in significant pre–post decreases in DT costs for gait velocity ($p < 0.001$, $d = 3.1$), stride length (−45%, $p < 0.001$, $d = 2.4$), and stride time (−44%, $p < 0.01$, $d = 1.9$). Training did not induce any significant changes ($p > 0.05$, $d = 0–0.1$) in DT costs for all parameters of secondary task performance during standing and walking. Training produced significant pre–post increases ($p = 0.001$; $d = 1.47$) in secondary task performance while sitting. The observed increase was significantly greater for the ST training group ($p = 0.04$; $d = 0.81$). For standing, no significant changes were found over time irrespective of the experimental group. We conclude that adolescents showed impaired DT compared to ST walking but not standing. ST and DT balance training resulted in significant and similar changes in DT costs during walking. Thus, there appears to be no preference for either ST or DT balance training in adolescents.

Keywords: postural control, cognitive performance, attentional demand, dual-task costs, cognitive interference

INTRODUCTION

Previously, human postural control has been considered an automatic task that requires minimal cognitive demand. However, research using dual-task (DT) paradigms showed that cognitive resources are needed to control standing (Palluel et al., 2010) and walking (Krampe et al., 2011) in children and adolescents. During everyday activities, adolescents often encounter situations involving the concurrent performance of attention-demanding tasks while standing or walking. For example, they may walk through crowded places or cross busy streets on their way to school while concurrently paying attention to other people, street lights, cars, cell phones. Thus, their attentional capacity has to be adequately divided between the primary (postural) and the secondary (cognitive) task to allow a safe way to school. However, shared capacity may result in performance declines in the primary task, the secondary task, or in both tasks.

In general, numerous original articles (Boonyong et al., 2012; Hung et al., 2013) and review papers (Ruffieux et al., 2015) clearly revealed performance decrements during DT compared to single-task (ST) situations in youth. Based on a systematic analysis of the literature on DT performance during lifespan, Ruffieux et al. (2015) reported slower gait speed, shorter stride length, and larger postural sway in DT compared to ST conditions in youth, young and old adults. More specifically, the authors identified impaired DT balance performance (one-legged stance) particularly in youth (age: < 8–13 years) compared to young (age: 19–35 years) and old adults (age: > 59 years). It has to be noted though that the authors rated the available evidence in youth as inconclusive (Ruffieux et al., 2015). In children aged 8–9 years, cross-sectional studies (Beurskens et al., 2015, 2016a) also revealed significant decreases in gait velocity, stride length and cadence while walking in DT compared with ST conditions. Within the youth age group, Palluel et al. (2010) compared ST and DT balance performance in 12–15-year-olds versus 17-year-olds. The study revealed larger postural sway and higher sway velocity in the younger age group. Those decrements in walking performance may significantly increase potential risks during ambulation (e.g., when crossing a street and talking to a classmate or looking at a cell phone).

Many studies investigating DT performance calculated dual-task costs (DTC) to describe performance differences between ST and DT conditions in youth (Schaefer et al., 2008; Krampe et al., 2011). DTC yield one single measure rather than utilizing ST and DT performance separately. Positive values indicate deteriorated performance from ST to DT condition that is, declines in the primary postural task and/or the secondary cognitive/motor task during DT compared to ST condition. Negative values on the other hand represent better performances (Somberg and Salthouse, 1982). Previously, the occurrence of DTC have primarily been explained by limited cognitive capacities (Pashler, 1994) or cognitive interference when two tasks share the same processing resources (Wickens, 1984). More recently, concurrent performance models of multitasking have focused on the use of multiple resources (e.g., the "4-D multiple resource model" (Wickens, 2008), "model of *threaded cognition*" (Salvucci and Taatgen, 2011)]. In contrast to single-channel and specifically bottleneck theories, resource models incorporate the idea that the available somewhat limited resources can be scheduled and allocated to specific task processing, i.e., shared between multiple tasks in varying proportions (cf. Fischer and Plessow, 2015).

The model of threaded cognition (Salvucci and Taatgen, 2011), for example, accounts for dual-task interference patterns by adducing multiple resource constructs within perceptual modalities (cf. Wickens, 2008). The main premise of the model is that multiple threads of cognitive processing can be active at the same time. However, multitask interferences occur when (multiple) threads or goals are simultaneously active and require the same cognitive resource at the same time. Consequently, one thread must wait and its performance will be adversely affected (cf. Salvucci and Taatgen, 2011).

Difficulties in allocating attentional resources to two tasks or the inability to manage additional cognitive demands caused by limited information processing capacity may provoke DTC in postural control. In adolescents, deficits in postural control have primarily been attributed to immaturity of the visual and vestibular systems which represent two major afferent systems that contribute to postural control (Hirabayashi and Iwasaki, 1995; Steindl et al., 2006). Thus, there is a need to elucidate whether DT balance performance can be improved through adequate training regimes in youth.

There is ample evidence on the general effectiveness of balance training on balance performance in youth as indicated in randomized controlled trials (Granacher et al., 2010a; Pau et al., 2012; Donath et al., 2013) and recent systematic reviews (Gebel et al., 2018). In an attempt to extend the findings of Granacher et al. (2010a) who demonstrated that balance training is suitable to enhance ST postural control, specifically designed intervention programs during PE may have the potential to improve postural control not only in ST but also in DT situations. However, to the authors' knowledge, there are currently no studies available that examined the specific effects of ST versus DT balance training in youth, especially concerning dual-task performance. Hence, our rationale is largely grounded on studies using other cohorts (i.e., seniors). Of note, the general effects of balance training on balance performance are well documented in seniors (Lesinski et al., 2015). In terms of the specific effects of ST versus DT balance training in old adults, Silsupadol et al. (2009a) reported that DT but not ST balance training resulted in improved DT balance performance in the form of faster habitual gait speed while performing an arithmetic interference task. However, the specific effects of ST versus DT balance training on DT performance have not yet been examined in youth. Hence, this study design follows the previously introduced approach from Silsupadol et al. (2009a) in geriatric populations and translates it from seniors to youth. In addition, there is evidence from adult studies that DT balance training may be superior to ST balance training in improving DT performance (Wollesen and Voelcker-Rehage, 2014). Thus, in order to decrease adolescents' DTC in balance performance, DT balance training might be an effective tool to improve the capacity to perform a motor and cognitive task concurrently by minimizing the cognitive overload.

Therefore, the main objectives of this study were (i) to examine static and dynamic balance performance under ST and DT conditions in healthy adolescents, (ii) to study the effects of traditional ST versus DT balance training in adolescents on static and dynamic balance under ST and DT conditions (i.e., standing/walking while concurrently performing an arithmetic subtraction task). With reference to the relevant literature (Boonyong et al., 2012; Hung et al., 2013; Wollesen and Voelcker-Rehage, 2014; Ruffieux et al., 2015), we expected impaired standing/walking performance during DT compared to ST balance performance in adolescents. We further hypothesized that DTC in static and dynamic balance is particularly reduced following DT balance training. In accordance with the principle of training specificity (Behm, 1995), we expected larger effects for static (i.e., standing) compared with dynamic (i.e., walking) balance because both balance training protocols primarily consisted of static balance exercises during standing on stable (i.e., gym floor) and unstable surfaces (i.e., balance pads) while balancing only (ST group) or while performing secondary tasks during the performance of balance exercises (i.e., DT group).

TABLE 1 | Participants' characteristics (mean ± standard deviation).

	Total (N = 28)	ST-BAL (n = 13)	DT-BAL (n = 15)
Sex (m/f)	13/15	6/7	7/8
Age (years)	13.3 ± 0.5	13.0 ± 0.3	13.4 ± 0.6
Body height (cm)	156.0 ± 7.1	155.9 ± 5.4	155.0 ± 9.0
Body mass (kg)	43.8 ± 8.1	41.5 ± 6.3	45.9 ± 9.9
BMI (kg/m^2)	18.0 ± 3.1	17.0 ± 2.1	19.1 ± 3.9
Physically active (%)	67.9	61.5	73.3
Membership in sport clubs (%)	50	46.2	53.3
School grades (range)			
German	1 (1–3)	1 (1–2)	1 (1–3)
Math	2 (1–4)	2 (1–3)	2 (1–4)
English	1 (1–4)	1 (1–3)	1 (1–4)

BMI, body-mass-index; ST-BAL, single-task balance training group; DT-BAL, dual-task balance training group; f, female; m, male; school grades are displayed as median (range).

MATERIALS AND METHODS

Participants

Twenty-eight healthy adolescents were recruited from a primary school located in the state of Brandenburg (City of Potsdam), Germany. Their characteristics are displayed in **Table 1**. Participants had no known neuromuscular or orthopedic disorders that might have affected their ability to perform the experiment. None had participated in research on posture or cognition within the preceding 6 months. Fourteen out of 28 enrolled participants were active members in sports clubs and 19 participants reported to be regularly engaged in self-organized physical activities (cycling, home workouts, or running). An a priori power analysis using two groups and a repeated measure ANOVA design yielded a total sample size of $N = 28$ (effect size = 0.25, $\alpha = 0.05$), with an actual power of 0.8 (critical F-value = 4.23). Effect size was based on a study that examined the effects of balance training on postural control in adolescents (Granacher et al., 2010a). The Human Ethics Committee at the University of Potsdam approved the study protocol (reference number: 04/2014). Before the start of the study, each participant and their parents/legal guardians read, concurred, and signed written informed consent. All procedures were conducted according to the latest version of the Declaration of Helsinki.

Data Registration

Testing procedure included the assessment of static and dynamic postural control in ST and DT situations. During ST conditions, only the respective motor or cognitive task had to be performed, whereas during DT conditions, participants were asked to concurrently perform an attention-demanding interference task (i.e., to recite out loud serial subtractions by 3, starting from a random number between 300 and 900). When DT methodology was used, participants were instructed to do both tasks as best as they can and thus give equal priority to both tasks in order to create real-life conditions. A similar procedure has been applied previously (Granacher et al., 2010b). The order of all experimental conditions was counterbalanced across participants and the assessors were blinded regarding group allocation.

Assessment of Static Postural Control

Static postural control was assessed using a three-dimensional force plate (Leonardo Mechanograph GRFP, Novotec Medical, Germany). The force plate consisted of eight sensors with a sampling rate of 800 Hz per sensor and registered center of pressure (CoP) displacements in medio-lateral (ML) and anterior-posterior (AP) direction. Participants were instructed to stand on their dominant leg (as assessed by the lateral preference inventory) (Coren, 1993). The non-supporting limb was flexed 45° at the knee, hands were placed akimbo and gaze fixated at a cross on a nearby wall. The length of standing trials was standardized to 30 s each. Excellent intra- (ICC = 0.97; 95% CI: 0.91–0.99) and intersession (ICC = 0.94; 95% CI: 0.84–0.98) reliability were reported for the one-legged stance (Muehlbauer et al., 2011). High interrater (ICC = 0.87–0.99) and test–retest (ICC = 0.59–0.99) reliability for the one-legged stance was reported in children (Atwater et al., 1990). Total CoP displacements were computed according to the following formula: $CoP[mm] = \sqrt{CoP_{AP}^2 + CoP_{ML}^2}$. CoP_{AP} represents CoP displacements in anterior–posterior and CoP_{ML} represents CoP displacements in medio-lateral direction. In addition, *CoP velocity*, indicating the total distances covered by the CoP divided by the duration of the sampled period and *sway area*, representing the ellipse area covered by the trajectory of the CoP were calculated (Schubert and Kirchner, 2014). Participants performed one trial in ST and one trial in DT condition.

Assessment of Dynamic Postural Control

Gait performance was registered using a 10-m instrumented walkway (OptoGait, Microgate, Bolzano, Italy). The OptoGait-System is an opto-electrical measurement device consisting of light-transmitting and -receiving bars. Each bar is 1 m in length and composed of 96 light emitting diodes transmitting to an oppositely positioned bar. With a continuous connection between two bars, any break in connection can be measured and timed. Participants' spatial and temporal gait characteristics were registered at 1,000 Hz. The OptoGait-System demonstrated high discriminant (error: $< 2\%$) and concurrent validity (ICC: 0.93–0.99) with a validated electronic walkway (GAITRite®-System) for the assessment of spatio-temporal gait parameters in healthy participants (Lienhard et al., 2013). Excellent intra-class correlation coefficients [ICC (2, 1) = 0.929–0.998] and coefficients of variation (CV_{ME} = 0.32–11.30%) were previously reported (Lee et al., 2014). Excellent test-retest reliability [ICC (3, 1) = 0.785–0.952] of the gait parameters measured by the OptoGait-System was demonstrated as well (Lee et al., 2014). *Gait velocity* was defined as distance covered per second during one stride. *Stride length* was defined as linear distance between successive heel contacts of the same foot, and *stride time* as time between the first contacts of two consecutive footfalls of the same foot. Participants performed one walking trial in ST and one trial in DT condition.

Assessment of Secondary Task Performance

For the assessment of secondary task performance, we registered the number of accurate calculations during DT conditions. If a participant miscalculated, the false calculation was noted. When correctly continuing the serial 3 subtraction, only one error was noted (no consequential errors were registered). Additionally, participants were asked to perform as many calculations as possible in 30 s while seated (i.e., ST condition). To compare secondary task performance across conditions (i.e., seated, standing, walking), calculations per second were used for our statistical analyses.

Balance Training Programs

In a quasi-experimental approach, two school classes were randomly assigned to either perform ST balance training (ST-BAL) or DT balance training (DT-BAL). Thus, the class and not the single participant was our unit of analysis in order to minimize transfer effects through the exchange of training experiences between intervention and control participants within one class. Both groups performed a progressive balance training program for 8 weeks. The training session consisted of a ∼5 min child-oriented warm-up consisting of small games and a 15 min balance training program. Participants were supervised by an expert on balance training together with the PE teacher of the two classes so that the participant to supervisor ratio amounted to 1 (supervisor): 7 (participants). Both supervisors provided feedback on exercise technique and task execution. Training sessions were integrated into the regular PE lessons (total duration: 135 min/week) and conducted during the warm-up period. Each warm-up session lasted 20–30 min. Following balance training, both groups conducted the same curriculum during PE classes. Both balance training protocols primarily consisted of static balance exercises during standing on stable (i.e., gym floor) and unstable surfaces (i.e., balance pad). Training progression was realized by periodically increasing the demand of the balance exercises. Training progressed from static bipedal (e.g., leaning forward/backward/side-ways) to static unipedal exercises (e.g., one-legged stance). The difficulty level was gradually increased by instructing the participants to perform the exercises with or without the help of their arms, their eyes opened or closed and/or on unstable training devices (i.e., soft mats, ankle disks, balance boards, air cushions). Occasionally, a few dynamic balance exercises (e.g., twisting jumps, stabilizing balance in one-legged stance after high knee running) were implemented. The ST-BAL group performed balance exercises only, whereas the DT-BAL group additionally integrated primarily attention-demanding cognitive (e.g., counting backward, naming objects, spelling, etc.) and/or occasionally motor interference tasks (e.g., juggle, roll a ball backward/forward with the free leg, etc.). Different secondary tasks were included in the training protocol that were not part of testing. The rationale behind this approach was to conduct a child-oriented and enjoyable training program for youth (cf. Wälchli et al., 2017) and to examine whether potential transfer effects occur. According to established dose-response relations in balance training, participants conducted four sets of 20 s for each exercise with 1 min rest between sets (Lesinski et al., 2015). Both legs were alternately exercised during one-legged stance.

Statistical Analyses

Data are presented as mean values and standard errors. One way analyses of variances (ANOVA) with repeated measure on Condition (ST vs. DT) were used to identify baseline differences in static and dynamic postural control between conditions. Participants' performances in ST compared to DT condition were analyzed separately for each measure using baseline values of the total group (N = 28). For further group analyses and to quantify participants' ability for executing two tasks concurrently, we calculated DTC for each participant and each outcome measure, according to the established formula (Somberg and Salthouse, 1982): $\text{DTC}[\%] = \left(\frac{\text{ST} - \text{DT}}{\text{ST}}\right) \times 100$, where "ST" represents participant's performance in single-task condition and "DT" represents participant's performance in dual-task condition. Positive DTC values indicate DT-related performance impairments and negative DTC values indicate improved performance during DT as compared to ST conditions. Separate 2 (Time: pre, post) × 2 (Group: ST-BAL, DT-BAL) ANOVAs with repeated measure on Time were computed to examine performance changes following training and univariate ANOVAs with repeated measure on Time (pre, post) were used to examine potential learning effects in the cognitive interference task. Effect sizes were determined by calculating Cohen's d-values (Cohen, 2013). All analyses were conducted using Statistical Package for Social Sciences (SPSS) version 23.0 (IBM Corp., New York, United States) and significance levels were set at $\alpha = 5\%$.

RESULTS

All participants received treatment as allocated. Overall, there were no statistically significant between group baseline differences in measures of age, anthropometrics (i.e., height, mass, BMI), and performance (e.g., static/dynamic balance performance, arithmetic secondary task) (all $p > 0.05$). Twenty-eight participants completed the balance training programs and none reported any training- or test-related injury. **Figures 1A–D** illustrate participants' baseline ST and DT performances. All analyzed walking parameters significantly deteriorated during DT compared to ST condition. That is, gait velocity ($p < 0.001$, $d = 5.1$) and stride length ($p < 0.001$, $d = 4.8$) decreased while stride time increased ($p < 0.001$, $d = 3.8$). **Table 2** describes results of measured ST and DT walking parameters at baseline. For standing (one-legged stance) and secondary task performance, none of the examined parameters was affected during DT condition (all $p > 0.05$, $d = 0.2–0.5$).

DTC in Dynamic and Static Postural Control Pre and Post Balance Training

Tables 3A,B describe pre- and post-intervention results and the corresponding ANOVA outcomes for parameters of postural control. **Figures 2A–D** display participants' DTC (note: for static postural control only DTC of total CoP displacements are shown). ANOVA yielded a significant main effect of Time for each gait parameter. That is, DTC decreased by 38–39% ($p < 0.001$, $d = 3.1$) for gait velocity, by 40–53% ($p < 0.001$, $d = 2.5$) for stride length, and by 40–50% ($p < 0.001$, $d = 2.0$) for stride time. No significant effects of Group and Time × Group interactions were observed for any of the examined gait parameters (all $p > 0.05$, all $d < 0.5$).

Regarding static postural control, our statistical analyses did not detect significant main effects of Time (all $p > 0.05$, $d = 0–0.2$) or Group (all $p > 0.05$, $d = 0.2–0.4$), nor significant Time x Group interactions (all $p > 0.05$, $d = 0.2–0.3$) for any of the examined parameters.

Secondary Task Performance Pre and Post Balance Training

Analysis of performance in the secondary task while sitting showed a significant and large main effect of Time ($p = 0.001$; $d = 1.47$) and a significant large sized Time × Group interaction ($p = 0.04$; $d = 0.81$). No significant main effects of Group were detected for all examined variables ($p = 0.30$; $d = 0.41$). Whereas the dual-task training group achieved

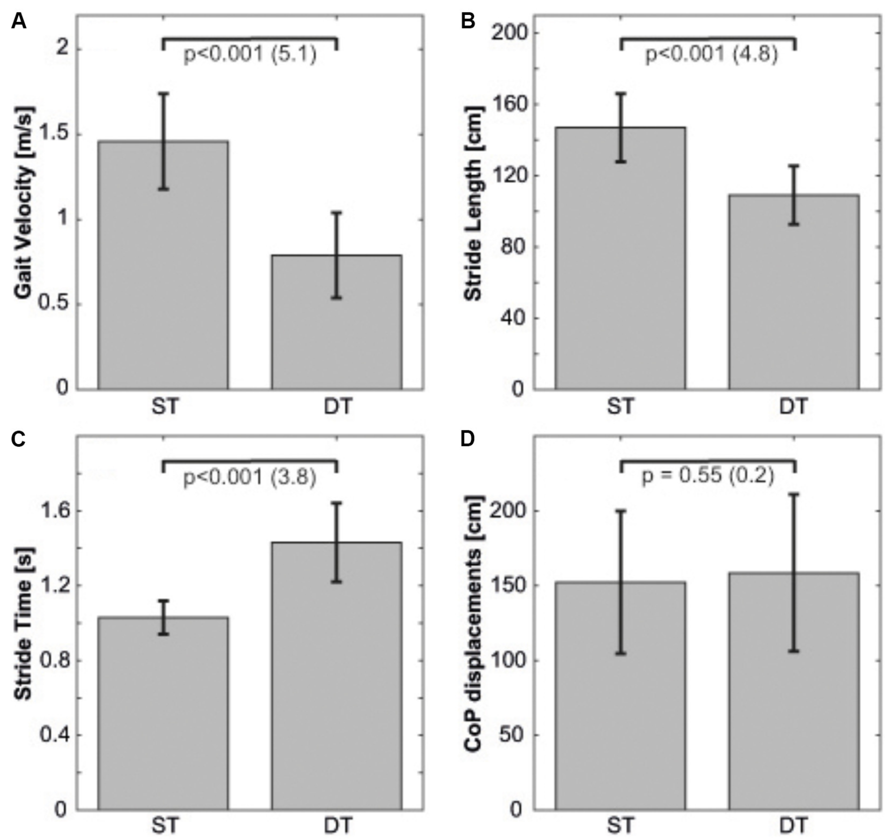

FIGURE 1 | Dynamic and static postural control during single-task and dual-task conditions at baseline, displayed separately for **(A)** gait velocity, **(B)** stride length, **(C)** stride time, and **(D)** total CoP displacements. Error bars represent the respective standard errors. Values in brackets represent Cohen's *d*. CoP, center of pressure; DT, dual-task; ST, single-task.

TABLE 2 | Outcome measures [ANOVA with within-factor Condition (ST vs. DT)].

	Means ± *SD*		*p*-value (*d*)
	ST	DT	
Gait velocity (m/s)	1.45 ± 0.3	0.77 ± 0.3	$p < 0.001$ (5.1)
Stride length (cm)	146.1 ± 18.6	108.3 ± 15.9	$p < 0.001$ (4.8)
Stride time (s)	1.03 ± 0.1	1.54 ± 0.5	$p < 0.001$ (3.8)

ST, single-task condition; DT, dual-task condition; Figures in square brackets represent Cohen's d.

0.28 correct calculations/s during baseline testing and 0.30 correct calculations/s during post-testing (+7.1%), the single-task training group improved significantly from 0.36 correct calculations/s to 0.40 calculations/s (+11.1%). Neither significant main effects of Time ($p = 0.478$; $d = 0.27$) or Group ($p = 0.149$; $d = 0.56$) nor Time × Group ($p = 0.446$; $d = 0.29$), Group × Condition ($p = 0.582$; $d = 0.21$) or Time × Condition ($p = 0.305$; $d = 0.40$) interactions during standing were found. Participants' DTC in secondary task performance during standing and walking are illustrated in **Figures 3A,B** and the respective ANOVA outcomes are displayed in **Table 3C**. The analysis yielded no significant main effects of Time (both $p > 0.05$, $d = 0$–0.1), Group (both $p > 0.05$, $d = 0.1$–0.6) or Time × Group interactions (both $p > 0.05$, both $d = 0.4$) for any of the examined parameters.

DISCUSSION

The present study examined differences in static and dynamic postural control during ST and DT conditions in adolescents aged 12–13 years. We additionally compared the effects of traditionally applied ST as compared to DT balance training on DTC in measures of dynamic (i.e., gait velocity, stride length, stride time) and static (i.e., total CoP displacement, CoP velocity, sway area) postural control and on secondary task performance (i.e., number of accurate calculations). The main findings of this study can be summarized as follows: (i) performances in walking but not standing deteriorated in DT compared to ST condition, (ii) both training regimes resulted in significant changes in measures of DTC during walking but not standing, and (iii) irrespective of the training regime, neither significant main effects of Time and Group nor significant Time × Group interactions were detected for (DTC in) secondary task performance.

ST vs. DT Performance at Baseline

Results showed that walking was affected when adolescents performed a concurrent arithmetic task. Gait velocity (ST: 1.45 ± 0.3 m/s; DT: 0.77 ± 0.3 m/s) and stride length (ST: 146.1 ± 18.6 cm; DT: 108.3 ± 15.9 cm) decreased and stride time (ST: 1.03 ± 0.1 s; DT: 1.54 ± 0.5 s) increased during DT compared to ST walking. These findings are consistent with previous studies investigating DT vs. ST performance in adolescents (Hung et al., 2013; Ruffieux et al., 2015). In general, the magnitude of the observed decrease in gait velocity in our study is higher than the changes found in a previous study (Boonyong et al., 2012), where adolescents aged < 16 years decreased their gait velocity by 4.5% when walking while concurrently conducting an auditory Stroop task. In the present study, adolescents reduced their gait velocity by 0.6 m/s (≙29%), indicating that the cognitive interference effects were substantial. Deficits in DT performance of adolescents might be explained by not fully developed structures (i.e., visual and vestibular systems) within the central nervous system (Riach and Hayes, 1987). More specifically, Hirabayashi and Iwasaki (1995) postulated that the proprioceptive system already matures between ages 3 and 4, while the visual system still develops until age 15. These findings were confirmed by Steindl et al. (2006).

With regard to DT balance performance, Palluel et al. (2010) argued that adolescents reach adult-like performance at the age of 14–15 years. Of note, our participants' mean age was 13.3 years. At this age, the postural control system is not yet fully matured (Woollacott and Shumway-Cook, 1990).

Findings from imaging studies provided evidence that the prefrontal cortex which is associated with executive functions and DT performance (Szameitat et al., 2002) is not fully developed at age of 14–16 years (Arain et al., 2013) as there is a developmental mismatch in brain maturation, with subcortical regions maturing during adolescence, whereas the prefrontal cortex does not reach a similar level of maturity until adulthood (Somerville et al., 2010; Mills et al., 2014). The (dorsolateral) prefrontal cortex plays a critical role for the regulation and processing of complex cognitive (mostly in executive functions) and motor tasks (Diamond, 2000; Liang et al., 2016). In a recent study, Beurskens et al. (2016b) examined the underlying neural correlates of single- and dual-task walking. Beurskens et al. (2016b) registered neural activation in frontal, central, and parietal brain areas using a mobile 64 channel EEG system. They found that average activity in alpha and beta frequencies was significantly modulated during both cognitive (i.e., participants were asked to respond to a low-pitched tone by pressing a button and inhibit their response to a high-pitched tone) and motor interference (i.e., participants held two interlocked sticks in front of their body which were not supposed to touch each other) walking conditions in frontal and central brain regions. More specifically, lower alpha activity in frontal brain areas was found when walking while concurrently performing the cognitive interference and the motor interference task. This is indicative of an increased cognitive load in the prefrontal cortex during dual-task walking (Beurskens et al., 2016b). The authors concluded that impaired motor performance during dual-task walking is mirrored in neural activation patterns of the brain, which complies with established cognitive theories arguing that DT situations overstrain cognitive capabilities, resulting in motor performance decrements (Beurskens et al., 2016b).

Thus, a decrement in performance during DT situations can most likely be observed due to limited cognitive capacity (i.e., "central overload") (Pashler, 1994). According to the single-bottleneck theory, the cognitive processes involved in maintaining balance and calculating could only proceed sequentially due to structural capacity limitations. This ultimately resulted in performance decrements (i.e., DTCs) especially in

TABLE 3 | Outcome measures (ANOVA with repeated measures on Time).

	ST-BAL (*n* = 13)			DT-BAL (*n* = 15)			*p*-value (*d*)		
	Pre	**Post**	**Δ**	**Pre**	**Post**	**Δ**	**Time**	**Group**	**Group × Time**
(A) Dynamic balance performance									
DTC – gait velocity (%)	42.7 (5.1)	25.9 (4.4)	−39	48.0 (3.1)	29.6 (3.9)	−38	< 0.001 (3.1)	0.39 (0.3)	0.69 (0.2)
DTC – stride length (%)	23.6 (3.0)	14.2 (2.6)	−40	26.8 (2.1)	12.5 (3.2)	−53	< 0.001 (2.5)	0.81 (0.1)	0.19 (0.5)
DTC – stride time (%)	34.4 (6.1)	17.2 (4.0)	−50	39.6 (4.3)	23.9 (3.9)	−40	< 0.001 (2.0)	0.22 (0.5)	0.92 (0)
(B) Static balance performance									
DTC – CoP displacement (%)	11.7 (11.5)	16.2 (8.9)	+38	5.1 (5.1)	7.7 (4.9)	+51	0.76 (0.1)	0.31 (0.4)	0.67 (0.2)
DTC – CoP velocity (%)	12.6 (11.7)	16.2 (8.9)	+28	6.2 (4.2)	5.8 (5.2)	−6	0.96 (0)	0.28 (0.4)	0.57 (0.2)
DTC – sway area (%)	26.6 (13.1)	10.7 (16.3)	−60	13.1 (14.6)	14.9 (15.2)	+14	0.63 (0.2)	0.59 (0.2)	0.40 (0.3)
(C) Secondary task performance									
DTC – calculations (stand) [%]	−10.1 (12.7)	2.6 (6.5)	+74	−16.6 (8.6)	−27.8 (10.9)	−68	0.85 (0.1)	0.14 (0.6)	0.33 (0.4)
DTC – calculations (walk) [%]	5.5 (16.3)	4.8 (8.0)	−12	8.3 (6.5)	−1.0 (9.2)	−112	0.98 (0)	0.78 (0.1)	0.28 (0.4)

Values represent means (standard error). Figures in square brackets represent Cohen's d. No group baseline differences were detected (all p > 0.05); CoP, center of pressure; DTC, dual-task costs; DT-BAL, dual-task balance training group; ST-BAL, single-task balance training group.

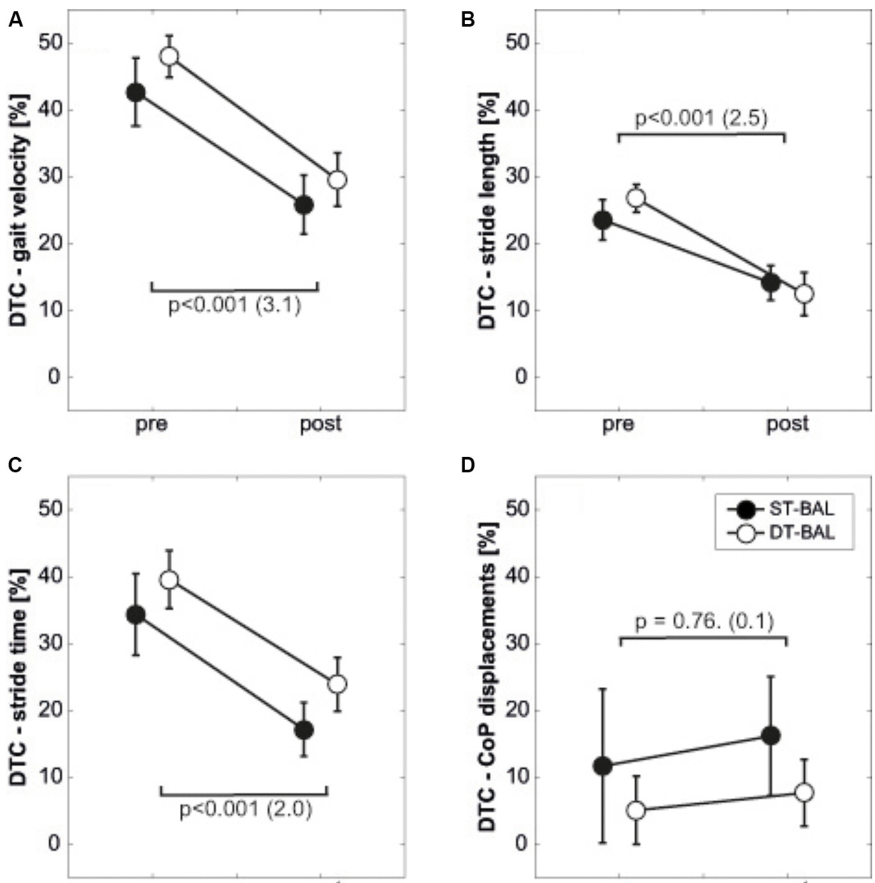

FIGURE 2 | Dual-task costs pre and post intervention, displayed separately for **(A)** gait velocity, **(B)** stride length, **(C)** stride time, and **(D)** total CoP displacements. Error bars represent the respective standard errors; CoP, center of pressure; DTC, dual-task costs; DT-BAL, dual-task balance training group; ST-BAL, single-task balance training group; *p*-values indicate the main effect of Time. Values in brackets represent Cohen's *d*.

task two in the sequence. However, the notion of structural capacity limitations for central processing stages (bottleneck) in multi-task situations has been debated intensively in recent years (e.g., Logan and Gordon, 2001; Navon and Miller, 2002; Fischer and Plessow, 2015). The central question revolves around whether cognitive processes related to different tasks proceed

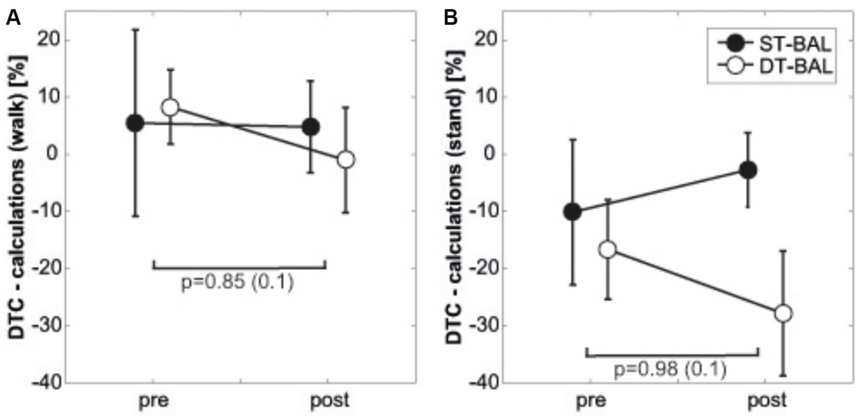

FIGURE 3 | Dual-task costs for secondary task pre and post intervention, displayed separately for **(A)** walking, **(B)** standing. Values in brackets represent Cohen's *d*; DTC, dual-task costs; DT-BAL, dual-task balance training group; ST-BAL, single-task balance training group.

only sequentially (one at a time), or can operate in parallel (simultaneously). In summary, it has been argued that parallel and serial processing of multiple tasks are not mutually exclusive and that shifting between more parallel and more serial task processing critically depends on the conditions under which multiple tasks are performed (cf. Fischer and Plessow, 2015). Hence, another theory should be taken into consideration.

Under the assumption of the multiple resource theory, division of (cognitive) capacity resources is possible and parallel processing can occur. According to this theory, DTCs arise when the processing of different task components require the same limited resources. The multiple-resource model of attention proposed by Wickens (1984) and the 4-D multiple resource model (Wickens, 2008), respectively, appear to be well-suited to provide detailed information regarding the occurrence of DT deficits in adolescents. The models essentially state that two tasks are most likely to interfere when they share the same pool of cognitive resources. Walking requires central and visual processing; subtracting numbers requires central as well as verbal processing. In other words, if two tasks are concurrently conducted with the primary task demanding postural control and the secondary task requiring cognitive processing, decrements in performance are likely to occur when task demands exceed cognitive capacities (Krampe et al., 2011; Beurskens et al., 2016a). Alternatively, applying the model of threaded cognition (Salvucci and Taatgen, 2011), the DTCs we observed could be explained similarly. In our case, the explanation would comprise that interferences occurred since the two threads or goals "maintaining balance or walking speed" and "correctly solving as many of the arithmetic tasks as possible" were active simultaneously. Moreover, both threads required (at least partly) the same resource at the same time, namely central processing. This adversely affected the performance of the thread that had to wait. For standing performance, no DT-related decrements were found in our study, indicating that the balance task might not have been sufficiently demanding to cause DT-related deficits. This assumption is supported by the fact that secondary task performance (i.e., number of correct calculations) during the standing task remained similar during DT as compared to ST situations. Similarly, for secondary task performance during walking, no DT-related losses in performance were observed.

Performance Changes Following ST and DT Balance Training

Previous studies showed that ST balance training is suitable to improve balance performance in adolescents (Granacher et al., 2010a; Pau et al., 2012). That is, 4 weeks of ST balance training (three sessions per week on unstable training devices) integrated into PE lessons significantly reduced postural sway. This reduction was not evident in an active control group (i.e., performing generic exercises during warm-up) (Granacher et al., 2010a). Similarly, 6 weeks of ST balance training (18 sessions for 20–30 min each) integrated in regular volleyball training significantly decreased total CoP displacements during bipedal and unipedal stance in 12-year-old adolescents compared to an active control group (i.e., attending regular volleyball training) (Pau et al., 2012). However, none of the studies examined ST balance training effects on DT performance in adolescents.

Following ST balance training, DTC in measures of walking improved in our study. That is, DTC decreased for gait velocity (−47%), stride length (−43%), and stride time (−50%). Similarly, DTC of gait velocity (−41%), stride length (−55%), and stride time (−38%) decreased following DT balance training. There is no study available that scrutinized the effects of ST and DT balance training on DT balance performance in adolescents. Thus, our findings have to be compared with results originating from studies with older cohorts. DT balance training has been shown to improve performance during DT situations in older adults (cf. Wollesen and Voelcker-Rehage, 2014 for a review). Adolescents still show maturational deficits in their motor-cognitive performance (Ruffieux et al., 2015) while older adults are in a state of age-related functional decline (Oberg et al., 1993). Thus, it is plausible to argue that similar adaptations following DT balance training can be expected in adolescents and seniors.

Silsupadol et al. (2009a) examined the effects of an individualized 4-week (three times per week for 45 min. each) DT compared to ST balance training on walking in older adults aged > 65 years. DT balance training included walking while counting backward, naming objects, or spelling words backward while ST balance training included walking exercises only. Results showed that ST and DT balance training were suitable to significantly improve dynamic balance performance (i.e., walking speed) (Silsupadol et al., 2009b) and center of mass position (Silsupadol et al., 2009a) during ST conditions. Yet, only DT balance training improved performance in DT walking conditions. These findings are in line with a recent review by Plummer et al. (2015) examining, among others, the effects of DT motor training on DTC in older adults. The authors found that DT training regimes resulted in significant improvements in DT gait speed, thus decreasing DTC. They concluded that DT motor training improved DT walking performance by increasing the speed at which individuals walk in DT conditions. This finding is in accordance with the principle of training specificity which denotes that the applied exercises during training should closely mimic the demands of sport-specific or everyday tasks (Behm, 1995). Concurring with this observation, Wollesen and Voelcker-Rehage (2014) showed evidence that improvements in DT performance are more pronounced following DT compared to ST balance training. Of note here, Wollesen and Voelcker-Rehage (2014) examined healthy old adults in their systematic review.

In our study, walking performance was significantly better following both, ST and DT balance training. A number of methodological reasons may account for the observed differences in study findings between Wollesen and Voelcker-Rehage (2014) and our study. While Wollesen and Voelcker-Rehage (2014) conducted their study in older adults, we examined adolescents aged 12–13 years. Given the different age group and differences in (included) experimental/study design between our study (adolescents; quasi-experimental design) and the studies used in Wollesen and Voelcker-Rehage (2014) systematic review (older adults; RCTs) the differences in the described findings seem to be explainable. In this regard, it appears to be plausible to argue that similar adaptations following DT balance training can be expected in adolescents and seniors. However, this needs to be verified in future studies. Thus, the differences in findings between our study and the mentioned systematic review may be explained by the fact that there are indeed great differences between the respective age groups after all and/or by the limitations of our (single) study (see below). For many years, the control of walking has primarily been seen as an automatic process. Today, it is well-known that attentional resources are necessary to effectively stabilize the body during standing and walking (Woollacott and Shumway-Cook, 2002). It has been shown that ST balance training modifies cortical plasticity (Taubert et al., 2010, 2011) and excitability (Taube et al., 2007; Taube, 2012). In fact, following 2 weeks of balance training [i.e., standing on a moveable platform (stabilometer)] increased gray matter volume in young adults in frontal and parietal regions of the brain (Taubert et al., 2010). Moreover, these authors found that white matter volume increased in the same spatial and temporal pattern. Over the 6 weeks balance training period, Taubert et al. (2010) further demonstrated that initial gray matter changes in sensorimotor-related regions decreased in the later learning phase, while gray matter in the prefrontal cortex continuously increased. These authors interpret their findings as the initial challenge of learning a complex motor skill and an important characteristic for entering later learning stages (Taubert et al., 2010). These results are indicative of training-induced modifications in central processing mechanisms following ST balance training. This assumption is supported by Taube et al. (2007), who found reduced cortical excitability and spinal reflex activity (Taube et al., 2008) following ST balance training. These authors hypothesized that ST balance training and the accompanied improvements in motor performance result in adaptations on the subcortical level of the brain (i.e., in basal ganglia and cerebellum). This hypothesis was supported by findings from Taubert et al. (2011) who reported increased gray matter volume in prefrontal and supplementary-motor areas and additionally, increased activity in subcortical brain regions following ST balance training. While structural changes in gray matter and functional connectivity alterations were most prominent during the first 3 weeks of training, changes in fronto-parietal functional connectivity and the underlying white matter structure developed gradually over the course of the 6 weeks of training (cf. Taubert et al., 2011). According to these authors, it appears that ST balance training induces a shift in activation from cortical to subcortical areas (cf. (Taube, 2012) for a review).

Similarly, DT balance training might induce improved task coordination skills when two tasks have to be performed simultaneously. In general, deficits in DT performance arise if an overload in cognitive capacities occurs (Pashler, 1991) or when two tasks share cognitive/sensory modalities and processing resources (Wickens, 1984). The efficacy of DT balance training might be based on an efficient integration and coordination of two concurrent tasks. During DT balance training, specific DT situations play a crucial role in the training process, which results in an improved performance in these particular tasks. Thus, ST and DT balance training in adolescents might free up central processing capacities and cognitive resources that can then be used to adequately adapt to DT situations while walking.

On the other hand, static postural control (i.e., one-legged stance) and secondary task performance in our study were not affected following ST and DT balance training. The former finding is in contrast to previously published studies in children (Donath et al., 2013) and adolescents (Granacher et al., 2010a; Pau et al., 2012). Granacher et al. (2010a) were able to show that 4 weeks of ST balance training during PE lessons resulted in significantly reduced postural sway in adolescents. However, the absence of improvements in static postural control in our study can primarily be seen as a result of the non-existent DT-related impairments at baseline (cf. **Figure 1D**). However, it was still surprising to see neither significant main effects of Time or Group nor Time × Group, Group × Condition or Time × Condition interactions during standing. We hypothesize that the secondary task might have been too easy for our participants which is why we could not detect interference during standing. This finding is supported by the fact that performance in the secondary task while standing improved following training (pre: 0.32 ± 0.16 correct calculations/s; post: 0.38 ± 0.18 calculations/s) while balance performance declined. The absence of improvements on secondary task performance following training in our study resembles previous findings. In a recent systematic review, Plummer et al. (2015) found that six out of nine studies on the effects of physical exercise interventions (ST/DT balance training, cardiovascular and strength training, multicomponent exercise program, DT treadmill walking) on DT walking performance in older adults reported no significant change in DT performance for the cognitive tasks. To explain the absent effects on cognitive task performance during DT, aspects of task similarity and training specificity have to be taken into consideration. Participants in the DT training group explicitly (but not exclusively) trained cognitive tasks (e.g., calculations or spelling) during DT balance training which is why they were used to these kind of tasks (task similarity). This in turn led to a higher level of automaticity in task execution. Thus, more resources were available for the other, non-cognitive tasks (i.e., maintaining postural control) (Agmon et al., 2015). Consequently, participants of the DT training group improved in postural control rather than cognitive performance following training. Similarly, the ST balance training in the ST training group led to a higher level of automaticity in task execution of the postural control task which in turn resulted in the improvements in DT performance (training specificity). Training-induced improvements in postural control in the form of increased task automatization may have allowed participants to better perform the cognitive tasks by using the gained resources and capacities that were previously needed to adequately control posture (Kramer et al., 1995).

Limitations

Four potential limitations of this study warrant discussion. First, no passive control group was included in this study. The inclusion of a passive control group is impossible in a school setting, as we cannot expect students and physical education teachers to stop conducting a warm-up program at the beginning of PE lessons. Also, preventing one class from conducting a warm-up program without performing balance exercises was not suitable since the development of postural control is a major part of the syllabus at this stage of PE. However, our aim was not to evaluate general effects of balance training in adolescents. It has previously been shown that balance training is effective and feasible in a school setting (Granacher et al., 2010a) and suitable to improve ST balance performance in adolescents (Granacher et al., 2010a; Pau et al., 2012). Thus, a passive control group was not needed in our study design. We wanted to specifically elucidate the effects of ST versus DT balance training in youth. A second limitation of our study is the implementation of only one trial during ST and DT condition to register standing/walking performance. This limitation was based on our experimental setting and its limitations. We performed all experiments during regular PE classes and thus only a limited period of time was available to conduct all needed measurements. However, if a trial failed, the measurement was repeated to ensure one valid trial per condition for each participant. However, the use of one trial in the one-legged stance and OptoGait 10 m walkway test setting appears to be justified given the excellent reliability values that were reported previously (Atwater et al., 1990; Muehlbauer et al., 2011; Lee et al., 2014). Another limitation of this study may be possible effects of task prioritization on the balance or cognitive performance under DT condition (e.g., see Broeker et al., 2018). However, previous studies (e.g., Wehrle et al., 2010) found that there are no statistically significant differences, neither in balance performance nor in cognitive performance, when instructed to prioritize task one, two or both equally. As this phenomenon seems to be relatively robust (cf. Siu and Woollacott, 2007; Schaefer et al., 2008; Wehrle et al., 2010), we assume that prioritization did not play a significant role in our study. Lastly, we used a group-based training approach limiting the adaptation of training contents to the individual needs of the participants. However, we chose to use the group-based setting since it resembled commonly established training or exercise protocols during PE classes. Typically, physical education is group-based in school settings and we did not want to alter those established structures.

CONCLUSION

Adolescents suffer from impaired balance performance while walking during DT compared to ST conditions. This supports the theory that maintaining postural control and solving cognitive tasks (e.g., subtracting numbers) require similar cognitive processing (cf. (Wickens, 1984) and that DT-related performance decrements occurred when task demands exceed cognitive capacities (cf. Pashler, 1991). Further, we conclude that both, ST and DT balance training resulted in significant changes in youth DT walking performance. Lastly, we could not detect any significant effects on DTC in secondary task performance and that is irrespective of the applied training regime.

In conclusion and with regard to the results of our study, there appears to be no preference for either ST or DT balance training in healthy adolescents.

AUTHOR CONTRIBUTIONS

All authors listed have made substantial, direct and intellectual contributions to the work, and approved it for publication.

FUNDING

This work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG, priority program SPP 1772: grants GR 3997/4-1, HE 7464/1-1, and RA1047/4-1).

ACKNOWLEDGMENTS

The authors would like to acknowledge the Open Access Publishing Fund of the University of Potsdam supported publication of this work.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 25 May 2018
doi: 10.3389/fpsyg.2018.00714

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Empirical Support for 'Hastening-Through-Re-Automatization' by Contrasting Two Motor-Cognitive Dual Tasks

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OPEN ACCESS

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *06 October 2017*
Accepted: *23 April 2018*
Published: *25 May 2018*

Citation:
Langhanns C and Müller H (2018) Empirical Support for 'Hastening-Through-Re-Automatization' by Contrasting Two Motor-Cognitive Dual Tasks. Front. Psychol. 9:714. doi: 10.3389/fpsyg.2018.00714

Motor-cognitive dual tasks have been intensely studied and it has been demonstrated that even well practiced movements like walking show signs of interference when performed concurrently with a challenging cognitive task. Typically walking speed is reduced, at least in elderly persons. In contrast to these findings, some authors report an increased movement frequency under dual-task conditions, which they call *hastening*. A tentative explanation has been proposed, assuming that the respective movements are governed by an automatic control regime. Though, under single-task conditions, these automatic processes are supervised by "higher-order" cognitive control processes. However, when a concurrent cognitive task binds all cognitive resources, the automatic process is freed from the detrimental effect of cognitive surveillance, allowing higher movement frequencies. Fast rhythmic movements (>1 Hz) should more likely be governed by such an automatic process than low frequency discrete repetitive movements. Fifteen subjects performed two repetitive movements under single and dual-task condition, that is, in combination with a mental calculation task. According to the expectations derived from the explanatory concept, we found an increased movement frequency under dual-task conditions only for the fast rhythmic movement (paddleball task) but not for the slower discrete repetitive task (pegboard task). fNIRS measurements of prefrontal cortical load confirmed the idea of an automatic processing in the paddleball task, whereas the pegboard task seems to be more controlled by processes interfering with the calculation related processing.

Keywords: hastening, automatization, rhythmic movement, motor-cognitive dual task, upper limbs, mental calculation, fNIRS

INTRODUCTION

Every-day life comprises numerous situations in which we move our body while we are performing more or less challenging cognitive tasks in parallel. We are involved in a conversation while we walk, we cut vegetables while mentally calculating quantities of ingredients, we try to retrieve the remnants of the mental roadmap of the city we revisit after so many years while we drive the car, etc. Many experimental studies have looked at how both tasks interact in such situations, which will be called motor-cognitive dual task (MCDT) henceforth. These studies show that even when well-practiced movements like walking are involved, motor and cognitive tasks interfere, meaning that performance in the MCDT condition suffers compared to when each of the tasks is performed in isolation (ST: single task condition; e.g., see review by Woollacott and Shumway-Cook, 2002). Under MCDT conditions, motor tasks show reduced movement speed (walking: Holtzer et al., 2011; manual joystick tracking: Gazes et al., 2010) or higher variability (finger tapping: Wu et al., 2013; isometric manual force production: Mandrick et al., 2013a).

However, this interference is not pervasive, as for example Lindenberger et al. (2000) observed pronounced interference effects in older adults whereas younger adults did not show any sign of it in the same MCDT situation. This is interpreted as the result of a 'posture-first' prioritization strategy. In case of a competition for processing resources, older subjects give higher priority to the walking task in order to prevent falls (Li et al., 2001). This interpretation is supported by studies demonstrating that the prioritization is stronger if the 'postural threat' is increased (Lajoie et al., 1996; Brown et al., 2002; Gage et al., 2003).

However, explicit instruction to prioritize tasks may modulate this interference profile (Yogev-Seligmann et al., 2010). In these studies, walking speed is used as performance criterion indicating interference. Yet, even when walking speed was fixed by having subjects walk on a treadmill with constant velocity, interference by concurrent cognitive task could still be observed. Subjects reduced their step frequency at the cost of producing larger step lengths (Li et al., 2012). In situations with scarce processing capacity, prioritizing the motor task and allocating additional control resources to it, leads to reduced movement frequencies rather than a reduced movement amplitude.

Interestingly and in contrast, some researchers report an increase in movement frequency under dual-task conditions. In a study by van Impe et al. (2011), subjects drew circles within given space limits while concurrently performing a mental arithmetic task. Both, old and young subjects increased frequency of drawing movements under MCDT compared to ST conditions, which is interpreted as increased automatic control of the motor task when overall cognitive processing requirements are increased. Johannsen et al. (2013) had subjects perform ankle movements paced by a metronome while being engaged in *n*-back tasks of increasing difficulty. They observed an increase in movement frequency with increasing *n*-back difficulty. In addition, peak angular velocities were more regular with increasing velocity. However, with higher cognitive load, ankle movements were less strictly synchronized with the pacing stimulus (increased standard deviation of timing errors).

The increased movement frequency is called (involuntary) *hastening* by the authors and interpreted with "re-automatization." When general cognitive processing capacities are occupied by an additional cognitive task, the motor task returns to a more or less automatic regime, relinquishing online control of synchrony with the pacing stimulus. By this, the system may drift toward a natural or preferred frequency. Hastening arises, when this eigenfrequency is faster than the pacemaker. This explanation of the hastening effect is based on three essential assumptions: (i) the existence of two different control regimes, an automatic and a cognitively controlled mode of operation, (ii) the idea that the processing of a cognitive secondary task interferes with this latter cognitive motor control processes, and (iii) the assumption that the automatic process controls the movement less strictly, that is, corrects errors less frequently and extensively.

Evidence for the existence of two motor control regimes for repetitive movements, an automatic and a cognitively controlled regime according to (i), where only the cognitive control mode shows interference under MCDT conditions according to (ii) comes from a study by Soylu and Newman (2016). They observed underadditive effects in brain activation in an fMRI study where subjects had to perform finger-tapping movements under ST and MCDT conditions (calculation). Based on this observation, they suspect that finger movements are controlled more automatically under MCDT conditions than under ST conditions. Holm et al. (2017) also studied tapping movements in continuation of a pacing signal. Increasing the load of a cognitive secondary task led to an increase in movement variability. However, this was only observed for movement frequencies higher than 1 Hz but not for lower frequencies. Interestingly, other authors also mention a threshold of 1 Hz as critical boundary between an automatic control of time intervals below 1 s and a rather cognitively controlled timing mode for above-second durations (Rammsayer and Troche, 2014). The assumption of two separate timing control mechanisms is also supported by physiological evidence, suggesting that automatic timing is controlled in motor areas, whereas cognitive control involves prefrontal areas (Lewis and Miall, 2003).

Furthermore, this differentiation also relates to another body of work, postulating different control structures (primitives), operating in different brain regions for rhythmic and discrete movements (Schaal et al., 2004). In this framework, discrete movements are defined as movements including postures at least before and after the movements and rhythmic movements are thought to be "recurrent movements with no stops" (Hogan and Sternad, 2007). In a study by Park et al. (2017), subjects were no longer able to perform oscillatory movements between two horizontal targets rhythmically and smoothly when the movement was gradually slowed down from 1 to 6 s per cycle.

Evidence in favor of assumption (iii) comes from work by Balasubramaniam et al. (2004). They find larger irregularities in trajectories of movements being performed in synchrony with a pacing signal compared to a condition without external pacing. These modulations of the movement patterns are likely to result from error compensation since the durations of movement phases show negative correlations. Importantly, this effect was modulated by movement frequency, the fastest movements showing the least amount of corrections. We have already mentioned that the amount of cognitive involvement in movement control might not just be modulated by movement duration but also depend on whether the movement can be considered as rhythmic or discrete. Indeed, Elliott et al. (2009) show stronger and faster corrections in discrete than in continuous (rhythmic) movements.

In the light the theoretical ideas and empirical observations mentioned so far, we may now have clearer expectations, under which conditions, the addition of a secondary cognitive task will severely impair performance in a motor task and in which settings interference should be smaller. One can even think of situations, where an additional cognitive task might even be beneficial. If motor performance is better when the automatic control regimes is left on its own and not disturbed by higher-order cognitive control, detracting the cognitive control away from the motor task by keeping it occupied with the cognitive task might be beneficial. A similar idea has already been propagated to explain the beneficial effect of an external attentional focus (Wulf, 2013) or the concept of 'errorless learning' (Maxwell et al., 2001; Poolton et al., 2005). The observed hastening effects, that is, the increased movement frequencies under MCDT conditions might be just one example of these boosting effects.

Yet, even though results reached significance, hastening effects were rather small. However, in most cases, the hastening effect was not the main focus of the experiment but rather a surprising side-effect, noticed by the researchers. Hence, the design was not always adequate to display the effect in the clearest possible way. In the studies by Balasubramaniam et al. (2004), van Impe et al. (2011), and Johannsen et al. (2013) the movement was externally paced. Therefore, any tendency to increase movement frequency is in conflict to the instruction to keep the beat. Remarkably, a tendency for hastening was still observed, even in spite of these strong diminishing factors.

In the present study, we wanted to see, whether the effect can be replicated under conditions designed to reduce diminishing factors and whether we can find support for the hypothetical explanation stated above. Due to this explanatory idea, hastening of repetitive movements should be strongest, when automatic control processes are involved. This should be more likely, for faster (period < 1 s) rhythmic movements, compared to slower (>1 s per cycle) discrete movements. In order to avoid the speed stabilizing effect of an external pacemaker, no desired frequency should be enforced externally. Instead, we selected tasks, where the task dynamics define a natural frequency range. We opted to use a paddleball task as a fast rhythmic task and a pegboard task as a relatively slow discrete repetitive task. We are well aware of the fact, that movement frequency is not the sole difference between these tasks. The pegboard task requires grasping and release of small objects, whereas the paddle is kept in hand throughout the whole movement, The spatial goal for the hand movements is defined by the layout of the pegboard, requiring significant spatial accuracy, whereas the paddleball task stresses temporal accuracy. Any of these differences might lead to specific effects on performance under dual-task conditions. Therefore, any result of our experiment cannot be understood as final proof of the "hasting-through-re-automatization" hypothesis. Nevertheless, this hypothesis allows us to derive very specific expectations in our experimental setting. Besides the pure behavioral effect of increased movement frequencies, we will also look at physiological evidence related to the underlying assumptions regarding automatization.

In order to control whether automatized processing is facilitated by detracting cognitive surveillance we also measured activity in the right prefrontal brain area. Other studies used fMRI-technology for this purpose. However, this strongly limits movements to rather restricted body positions and small movements of distal effectors (fingers or feed). In a systematic review, Leone et al. (2017) argued that NIRS technology is also suitable to validly quantify cortical activation changes during ST compared to MCDT. Since, NIRS measurements are also possible in our less restricted tasks we opted to use this method in our experiment.

Taken together, characterizing the pegboard task as a (relatively) slow discrete repetitive task and paddleball as fast rhythmic movement allows us to derive very specific expectations regarding behavioral effects (movement frequency) and brain activation changes under MCDT conditions. The following experiment was designed to test these predictions empirically.

MATERIALS AND METHODS

Design

Given the theoretical background we have discussed so far, the frequency of a repetitive movement should be affected differently by a concurrent cognitive task depending on its frequency and its location along the discrete-rhythmic spectrum. In order to test this expectation, we selected two repetitive motor tasks, a paddleball task and a pegboard task, which should represent these categories. We measured subjects' performance in these tasks and in the cognitive task (calculation) under ST and MCDT conditions. We also looked at brain activity in prefrontal areas using NIRS. Conditions were tested in a complete within-subject design in counterbalanced order across subjects and task conditions. For sake of completeness, we have to mention that we also tested other motor tasks in combination with the calculation task under MCDT conditions with the same subjects in the same experiment. However, these were not related to the current research question and we do not have any indication that subjects' exposure to these additional conditions influenced the results reported here.

Motor Tasks

Paddleball (Paddleball UNO, Active People, Binningen, Switzerland) is a one-handed rhythmical bouncing game. A small rubber ball is connected to the center of a hand-held paddle via an elastic band. The task is to bounce the ball so that it is repeatedly propelled off the paddle, then retracted back toward the paddle surface by the elastic band (17 cm) where it is hit again, thus starting the next cycle. Bouncing the ball in succession for as many repetitions as possible requires a rhythmic back and forth movement of the paddle adjusted to the movements of the ball. Note, although ball and hand movements have to be in synchrony, no external pacemaker is involved. The frequency of movement cycles evolves from the dynamical interaction of propelling and retracting forces. The system has no strict eigenfrequency since the amplitude of the paddling movement is variable. However, typical driving frequencies for the task are around (5 Hz). A bout of successive paddling cycles can be continued as long as the ball hits the paddle after being retracted. If the ball misses the paddle, an interruption occurs. Subjects have to restart a new bout by initiating a next first hit of the ball. This can be accomplished by different maneuvers, which we do not describe here. In fact, after the familiarization trials, each subject was capable to initiate a new bout very quickly, however using his/her own preferred technique.

Subjects were asked to paddle with their right hand in an upright standing position for 60 s. They should try to stay in a paddling regime as long as possible. If a bout was interrupted, subjects were asked to start a new bout immediately. The task can be accomplished without necessarily visually fixating ball or paddle. Subjects were instructed not to control their movements visually, but rather look at a screen at eye level, positioned 50 cm in front of their eyes where the stimuli for the cognitive tasks were presented (**Figure 1A**). Movement frequency was measured acoustically based on the sound produced by each ball-paddle impact. Sound was recorded by an in-built computer microphone (8,000 Hz sampling rate, 8 bit per sample).

In the *pegboard task*, subjects sat at a table directly in front of a pegboard with nine holes arranged in a 3 × 3 square pattern (Jamar 9-hole peg test kit, Patterson Medical Ltd., Nottinghamshire, United Kingdom; **Figure 1B**). Nine cylindrical plastic pegs were placed in a hollow behind the board. Subjects were asked to use their right hand to put the nine pegs in the holes one by one. After completion, the pegs should be removed one by one until all pegs are in the hollow again. This filling and emptying of the holes should be continued without interruption throughout a period of 60 s. Note that movement frequency was also not externally paced in this task. The speed at which each single sub movement can be performed is at least partly curtailed by the distance traveled and the required precision at the endpoint according to Fitt's Law.

In order to allow this task also to be performed without visual control, subjects were encouraged to use the left hand to detect the next empty hole exploiting tactile information. This freed their gaze to look at a screen in 50 cm distance from the eyes. Performance was measured by the number of stuck resp. drawn pegs, which was counted by a research assistant.

Cognitive Task

The cognitive task was a mental subtraction task, presented on a screen. Subjects had to calculate the difference between a four-digit minuend and a two-digit subtrahend (e.g., 3543 – 67) as fast as possible and report the result verbally. Immediately after naming the result, a new digit pair was presented on the screen. Digit pairs were drawn from a list of selected 300 minuend-subtrahend pairs. The list did not contain digits equal to zero at the units and the tens position in neither minuend, subtrahend, or in the result in order to unitize difficulty. The digit pairs were presented in a single line in the format "3543 – 67" in the middle of the screen in white digits (~3 cm height) on a black background. Subjects were asked to correctly solve as many subtractions as possible within the 60 s trial. Our raw measure of calculation performance was the number of correct subtractions in this interval (numCLC).

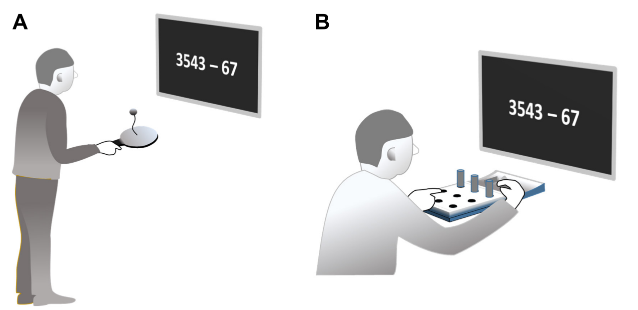

FIGURE 1 | Posture and set-up of the paddleball task **(A)** and of the pegboard task **(B)**.

Single and Dual-Task Conditions

The paddleball task and the pegboard task were executed in isolation (ST conditions, STpad and STpeg) and concurrently with the calculation task [dual-task conditions (DT), DTpad and DTpeg]. Under DT conditions, subjects were instructed to "perform both tasks as good as possible." The calculation task was also performed without concurrent repetitive movement (STclc). In the STclc condition subjects remained in the posture required by the previous motor task, that is, if the STclc condition followed the paddleball task, subjects remained in an upright freehanded stance whereas subjects remained seated when the STclc condition followed the pegboard task. We analyzed STclc performance separately for the seated and the standing conditions. However, we found no indication of systematic differences between conditions.

Participants

Fifteen students (nine females and six males; mean age = 27.1 years ± 7.1) participated in the study. All participants were right-handed according to their scores in the Edinburgh Handedness Inventory (Oldfield, 1971). The mean score was 88.7 ± 16.8. All subjects had normal or corrected to normal vision and self-reports indicated physical and mental health. All subjects gave written informed consent. Experimental procedures where in accordance with the declaration of Helsinki and were approved by the local ethics committee.

Procedure

Overall, each participant completed three sessions on three consecutive days, a familiarization practice on the first day and three task blocks on each of the ensuing 2 days. Each task block was limited to one specific motor task. Hence, only one of these task blocks was dedicated to the pegboard task and one to the paddleball task. As mentioned above, four additional task blocks involving further motor tasks were executed. Since they were irrelevant for the current question, they will not be described in detail. We counterbalanced the order of the six task blocks across participants, also leading to a counterbalanced order of the pegboard and paddleball task.

Each task block contained nine trials: Every trial lasted 60 s and was followed by 90 s of rest, allowing physical and mental recreation. Blocks included three trials of the given motor task (STxxx), three repetitions of the calculation task (STclc), and three repetitions of the MCDT combination (DTxxx).

The sequence of these nine trials within each task block was pseudorandomized to also counterbalance trial order within blocks across subjects and motor tasks.

To ensure that subjects were sufficiently familiar with the motor tasks when entering the task blocks on day 2, participants practiced each motor task three times for 60 s on day 1 under ST conditions. A reward (10, 20, 30 €) for the three best performers in the calculation task was announced to keep subjects' motivation high throughout the entire experiment.

Preprocessing of Behavioral Data

Paddling Performance

To record the series of paddleball hits we used the auditory signal and pre-processed it with Matlab 8.1 (MathWorks Inc., Natick, MA, United States). We filtered the signal with a fifth order, low pass Butterworth filter (cut off frequency: 10 Hz) to remove background noise and human voice. In the next step, all peaks indicating ball-paddle contacts were automatically detected, using a validated threshold. For analysis of paddling frequencies, we included bouts of at least five hits in a row, that is, it should last at least approximately 1 s. **Figure 2** shows individual paddling performances representing the longest paddling runs per trial and the summarized duration of all included paddling runs per trial, respectively. Paddleball frequency (frqPAD) was calculated by dividing the sum of all ball contacts across all (included) bouts by the respective summed duration of the (included) bouts. ΔfrqPAD is the difference between paddling frequencies between the STpad and the DTpad condition ($\Delta frqPAD = frqPAD_{\mathrm{DT}} - frqPAD_{\mathrm{ST}}$).

Pegboard Performance

The frequency of movements in the pegboard task (frqPEG) was calculated as the number of moved pegs divided by task duration (60 s). The final dependent measure regarding our hastening hypothesis was the difference in frequency between the STpeg and the DTpeg condition ($\Delta frqPEG = frqPEG_{\mathrm{DT}} - frqPEG_{\mathrm{ST}}$).

Calculation Performance

Taking the average number of correct answers per trial, under STclc condition subjects reached 4.2 ± 1.8 correct answers per minute. When concurrently playing paddleball, calculation performance changed to 3.6 ± 1.7 answers and it changed to 2.9 ± 1.5 correct responses during the pegboard task.

However, previous studies have shown that the number of correct subtractions in a 60 s trial (numCLC) substantially improves within 2 days of practice resulting in systematically higher performance with increasing trial number. This learning effect superimposes the effects of the actual task conditions and can be considered as systematic error variance in our case. We tried to eliminate this variance by fitting the calculation performance across trials within each subject with a logarithmic function (Newell et al., 2001). The residuals of this fit (resCLC) were then used to describe the effect of each test condition relative to the expected baseline performance after the respective amount of practice.

Measurement of Cortical Load

We recorded neural activity in the prefrontal cortex of the right hemisphere with a one-channel (three light sources

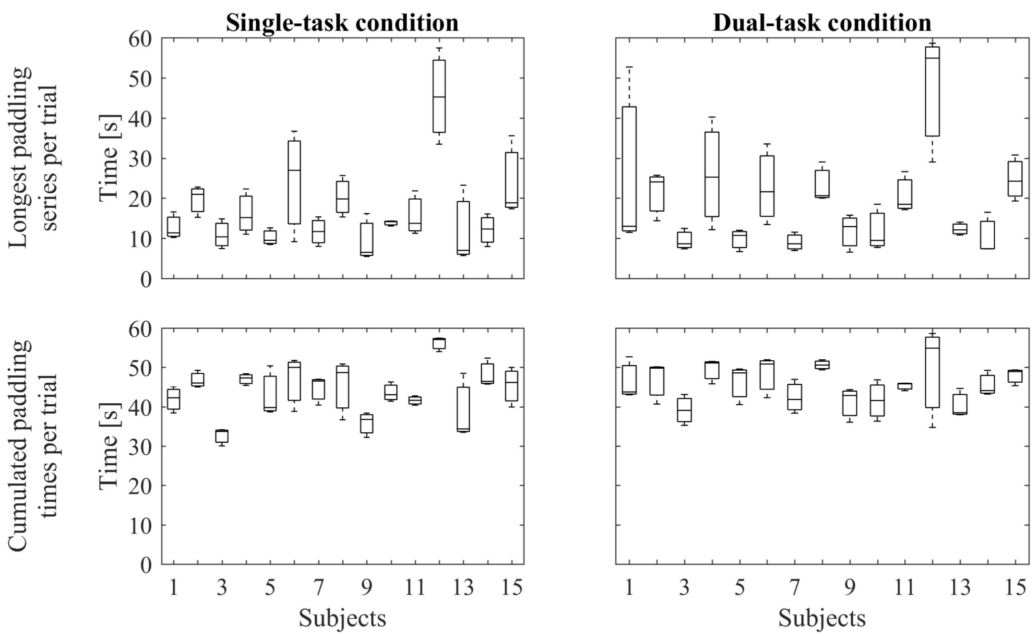

FIGURE 2 | Paddling performance. The upper row represents boxplots of the longest individual paddling run per trial under single-task condition **(Left)** and under dual-task condition **(Right)**. The lower row depicts boxplots containing the cumulated durations of the individual paddling runs per trial under single-task condition **(Left)** and under dual-task condition **(Right)**. In every boxplot, data from three trials are included.

placed in a row), continuous wave (758 nm, 853 nm) fNIRS device (PortaLite, artinis, Elst, Netherlands). We fixed the sensor at Fp2 according to the international 10–20 EEG-system. The fNIRS systems emits infrared light of different wave lengths and measures the concentration of oxygenated and deoxygenated hemoglobin in the region of interest (ROI) based on the refraction profile. Based on the measured hemoglobin concentrations, the amount of brain-activity changes in the region can be estimated. Due to the limited number of channels, we cannot observe a broader range of cortical processes during MCDT across the entire brain. Nevertheless, our single-channel system allows us to monitor a specific brain area to observe its specific involvement in executive functions in different experimental conditions. In previous experiments, brain activity in prefrontal region monitored in our study showed a characteristic profile of increase under MCDT conditions that led us to believe that the region is involved in executive functions and task monitoring in the type of tasks we use in our experiment (Leone et al., 2017).

We recorded NIRS data with a sampling rate of 25 Hz over the entire test session, including all trials. In a first step, trials were visually inspected for movement artifacts before passing the data on for further analyses. Since fNIRS-signal recording in some trials of seven subjects seriously suffered from paddling while calculating due to facial expressions they were unable to avoid, the respective trials were eliminated from further analysis. In a second step, artifacts from different sources (heartbeat, eye-blinks, and evoked potentials) were removed using a Butterworth bandpass filter 0.05–0.8 Hz. In the next step, we averaged the refraction signals from the three sources for both chromophores oxygenated (HbO) and deoxygenated hemoglobin (HbR). We used NIRSTORM[1] (Tadel et al., 2011) to perform the pre-processing of the fNIRS data. NIRSTORM is a publicly available plugin of the Matlab based software BRAINSTORM, used to analyze neurophysiological data.

It is not the absolute hemoglobin level but rather changes in hemoglobin concentration that are indicative of changes in brain activity due to the underlying neurovascular coupling. However, the change in concentration of the chromophores is only visible with a certain temporal delay. Therefore, we looked at the change in hemoglobin between trial start, that is, the average of the first 10 s (HbO_{0-10} resp. HbR_{0-10}) within a trial and the average of the last 10 s of a trial (HbO_{50-60} resp. HbR_{50-60}). We used these changes ($\Delta HbO = HbO_{50-60} - HbO_{0-10}$ and $\Delta HbR = HbR_{50-60} - HbR_{0-10}$) from start to end of a trial as measure of the cortical load induced by the respective condition (e.g., Mandrick et al., 2013b). Typically, an increase in HbO indicates an increase of cortical activity, whereas HbR should show a reciprocal decrease. Yet, this inverse relation of HbR is not always observed. Nevertheless, we follow the recommendations given by Obrig and Villringer (2003) and report the results of ΔHbR for sake of completeness, even though the hypotheses were less clear regarding this parameter.

[1] http://github.com/nirstorm

Statistical Analysis

We used one-tailed, one-sample *t*-tests to test the hypothesis whether movement frequency was increased under MCDT conditions for the paddleball task (ΔfrqPAD) and the pegboard task (ΔfrqPEG) separately. A one-factorial ANOVA with repeated measurements of the dependent variable "cognitive performance" (resCLC) across levels of the independent variable "task" (levels: STclc/DTpeg/DTpad) was computed to check to which extent cognitive performance is affected by the type of concurrent motor activity.

Whether changes in brain activity (ΔHbO, resp. ΔHbR) changed differently across conditions (independent variable "condition" with levels: STclc/STxxx/DTxxx), for the two motor tasks included in this study (independent variable "task," levels: Pegboard/Paddleball) was tested by a two-factorial ANOVA with repeated measurement on both factors. As already mentioned, our focus was mainly on the dependent variable ΔHbO. However, we will also report the equivalent results for ΔHbR. *Post hoc* analyses checked for differences using Bonferroni corrected *t*-tests. Significance level was set to $p = 0.05$ in all inferential statistical tests.

Further, we were interested in whether cognitive and/or motor performance is systematically related to cortical load. We quantified the strength of this connection by calculating correlations between the motor performance ($frqPAD_{ST}$, $frqPAD_{DT}$, $frqPEG_{ST}$, and $frqPAD_{DT}$) resp. cognitive performance ($numCLC_{ST}$, $numCLC_{DTpad}$, and $numCLC_{DTpeg}$) and the changes in prefrontal activation (ΔHbO) in a trial-wise manner. Each correlation reported in **Table 1** is based on *n* times three data pairs, resulting from *n* subjects with three trials per subject.

TABLE 1 | Correlations between cortical load and measures of cognitive and motor performance.

	Paddleball task block			Pegboard task block		
Condition	***n***	**Motor task**	**Cognitive task**	***n***	**Motor task**	**Cognitive task**
Single task	15	−0.11	−0.02	15	−0.50***	−0.12
Dual task	8	0.12	−0.17	15	−0.40**	−0.38**

*Cells differ in sample size (n) since seven subjects had to be excluded from analysis due to movement related artifacts in the fNIRS signal in the paddling dual-task condition. **p < 0.01, ***p < 0.001.*

RESULTS

Motor Performance

A *t*-test showed that movement frequency was significantly reduced under DT conditions compared to ST in the pegboard task [$t(14) = -7.289$, $p < 0.001$, **Figure 3**]. In contrast, as hypothesized, the paddleball task shows hastening, that is an increased movement frequency (on average 3% faster) under DT conditions [one-tailed analysis: $t(14) = 1.7662$, $p = 0.0496$]. Only two of our 15 subjects had substantially slower frequencies under DT conditions, whereas ten showed clearly increased frequencies. These were up to approximately 10% higher.

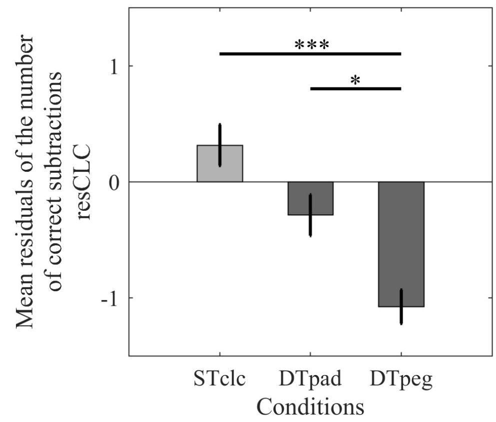

FIGURE 4 | Cognitive performance as mean relative number of correct calculations (resCLC) for single-task calculation (STclc) and for the two dual-task conditions (Paddleball: DTpad; Pegboard: DTpeg). Error bars represent standard errors of the mean. $^{*}p < 0.05$, $^{***}p < 0.001$.

Cognitive Performance

Cognitive performance (resCLC) differed significantly across tasks [$F(2,28) = 11.293$, $p < 0.001$, $\eta^2 = 0.446$; **Figure 4**]. *Post hoc* analyses indicated that performance suffered when the calculation task was performed simultaneously with the pegboard task compared to STclc ($p < 0.001$), whereas cognitive performance was not as strongly reduced when subjects paddled while calculating ($p = 0.23$). *Post hoc* test even revealed that cognitive performance is better while paddling compared to the pegboard condition (one-tailed analysis: $p = 0.0475$). According to these results, with respect to cognitive performance, the paddling condition is more similar to the STclc condition than to the pegboard condition.

Cortical Load

The ANOVA revealed no main effects for the dependent variable ΔHbO. There is neither a "condition" effect [$F(2,14) = 0.209$, $p = 0.814$, $\eta^2 = 0.029$] nor a "task" effect [$F(1,7) = 3.67$, $p = 0.564$, $\eta^2 = 0.050$]. However, as expected from our hypothesis, we found a significant interaction [$F(2,14) = 3.814$, $p = 0.048$, $\eta^2 = 0.353$]. Whereas cortical load is higher for the paddleball task under ST conditions ($\Delta HbO_{STpad} > \Delta HbO_{STpeg}$), the relation is reversed under DT conditions ($\Delta HbO_{DTpad} < \Delta HbO_{DTpeg}$; **Figure 5**). As a by-product, we also clearly see, that both STclc conditions show similar activation changes [$t(14) = 0.834$; $p = 0.4183$]. This observation indicates that cortical load does not depend on the posture taken while calculating (standing vs sitting). Interestingly, the cortical load in the DTpad condition is almost identical to the ST calculation condition (STclc; **Figure 5**). Apparently, paddling does not add any further cortical load to calculation.

In HbR we found a significant "task" effect [$F(1,7) = 8.799$, $p = 0.021$, $\eta^2 = 0.557$], but no effect of "condition" [$F(1.246,8.722) = 0.542$, $p = 0.519$, $\eta^2 = 0.072$] and no significant interaction effect [$F(2,14) = 1.504$, $p = 0.256$, $\eta^2 = 0.177$]. HbR was decreased more strongly in the paddleball task blocks

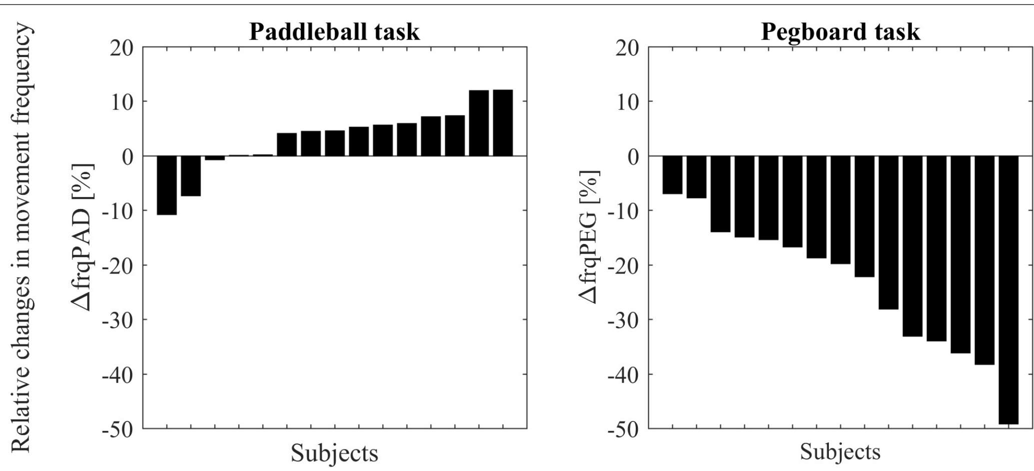

FIGURE 3 | Changes in movement frequencies from single to dual-task condition for all subjects. Subjects are ordered according to effect size. Results for the paddleball task (ΔfrqPAD expressed as % of individual mean frequency) are displayed on the left side. Results (ΔfrqPEG expressed as % of individual mean frequency) for the pegboard task on the right side.

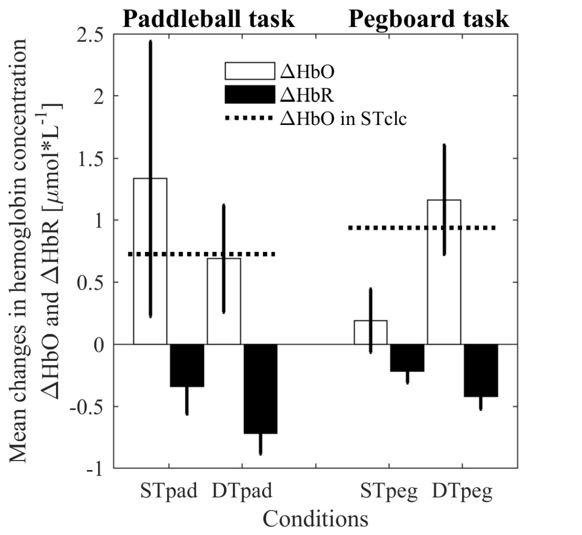

FIGURE 5 | Changes in hemoglobin concentrations for HbO (white bars) and HbR (black bars) as indication of processing load in prefrontal brain region for paddleball (pad) and pegboard (peg) task under single (ST) und dual-task (DT) conditions. The dashed horizontal lines represent cortical activity induced by single-task calculations (STclc). Error bars represent standard errors of the mean.

compared to the pegboard task block. However, as mentioned before, we did not have clear *a priori* hypotheses regarding the behavior of HbR.

Correlation Analyses

Table 1 shows correlation between the measures of cortical load (ΔHbO_{STpad}, ΔHbO_{DTpad}, ΔHbO_{STpeg}, ΔHbO_{DTpeg}, and ΔHbO_{STclc},) and measures of cognitive performance ($numCLC_{ST}$, $numCLC_{DTpad}$, and $numCLC_{DTpeg}$) resp. motor performance ($frqPAD_{ST}$, $frqPAD_{DT}$, $frqPEG_{ST}$, and $frqPAD_{DT}$). A negative correlation indicates that higher cortical loads are associated with lower performance. A previous study already showed that such a negative correlation is observed when the system operates at its limits, especially under DT conditions (Mirelman et al., 2014). The more performance falls back against an internal reference, the more prefrontal activity is increased during the 60 s interval. This is particularly the case for the pegboard task, relatively low motor performances are systematically linked to higher increases in activation in ST and in the DT condition. For the cognitive task, this connection can only be seen under DT conditions. Notably, for the paddleball task, neither of these relations are observed. We will discuss the relevance of these observations later in more detail.

DISCUSSION

The main goal of our experiments was to test specific predictions derived from the "hasting-through-re-automatization" hypothesis because of a particular classification of our experimental tasks. According to the literature, we expected a hastening effect, that is, a frequency increase under MCDT conditions only for one of our tasks, but not for the other, both belonging to different specific sub-classes of repetitive movements. According to the explanatory concept outlined so far, fast (>1 Hz) repetitive rhythmic movements should be controlled by an automatic control regime, which, however, is supervised by higher cognitive control processes. The involvement of the cognitive processes may lead to interference and probably also to a slower movement execution. Though, when a concurrent cognitive task binds all cognitive resources, the automatic process is freed from the detrimental effect of cognitive surveillance, allowing higher movement frequencies in that situation.

The results of our experiment were well in line with the expectations derived from this concept. We indeed observed a significant increase in movement frequency for the fast rhythmic movement (paddleball) under MCDT conditions in our experiment, thus replicating the findings reported by van Impe et al. (2011). In contrast, there was no such effect for the slow discrete repetitive movement (pegboard) in our experiment. Movement frequencies were clearly reduced under MCDT conditions in the pegboard task. The basic assumption underlying the explanation of this phenomenon is that both tasks are controlled by different types of control regime. This is confirmed by the observation that cortical load increases from STpeg to DTpeg but not from STpad to DTpad. In the latter case, one can even see a drop in prefrontal brain activation to the level of the cognitive ST. Actually this is exactly what you would expect, if the motor task runs automatically, that is, without any additional, prefrontally located cognitive processes being involved. By this, cortical activity is not upregulated to its limits in the paddleball task, even under MCDT conditions. Quite the contrary, in the pegboard task, adding the calculation task further increased cortical activity. As the correlational results show, this upregulation reaches a level where signs of saturation become visible. Surprisingly however, we also saw negative correlations between increase in prefrontal activity and motor performance in the ST–pegboard condition, where the absolute activation level was far from maximum. We do not know yet, how to explain this particular finding.

Even though the outcomes of our experiment are mostly well in line with our expectations, we need to mention some limitations of the current study. Most of the studies reporting hastening effects relied on an external pacemaker, potentially attenuating the hastening effect due to its normative function. In our study, we tried to overcome this limitation by using movements in which frequency is not externally set but rather the result of the internal and external task dynamics.

Another limitation of previous studies arises from the fact that they were mostly done in a brain scanner, allowing only very restricted movements. We wanted to overcome this limitation by studying rather naturalistic movements with larger movement extents. Consequently, we used fNIRS to still be able to collect physiological correlates of brain activity. Even though this was mostly successful, we have to admit that we encountered serious movement artifacts in some of our subjects when they paddled vigorously, particularly in MCDT condition. Only for about half of our subjects, the NIRS data were sufficiently clean, to include them in our analyses. This strongly reduced the power of our study. The other half showed strong head movement resp. strong mimic activity, partly due to the experienced satisfaction resp. dissatisfaction with subjects' own performance. This should be better controlled in future studies.

The recording of paddling movements based on the acoustic events was successful in registering ball impacts on the paddle. However, we were unable to analyze the recovery movements, that is, the movements used to initiate a new paddling bout, once the previous one could not sufficiently be continued.

Despite these methodological limitations, the overall result profile strongly supports the idea that a specific type of repetitive movements might indeed benefit when its control is freed from cognitive surveillance, which might be accomplished by another concurrently performed cognitive task. This is possible when an automatic control regime is available to master the task even in absence of higher cognitive control. However, when the repetitive task itself requires substantial cognitive control, an additional cognitive task will have detrimental effects. In our study, we have only looked at one representative of these movement classes and received a result profile that is well in line with the explanatory concept. Yet, alternative explanations based on further differences between the two tasks studied in our experiment cannot definitely be ruled out. Therefore, further empirical evidence is required to substantiate the "hasting-through-re-automatization" hypothesis.

AUTHOR CONTRIBUTIONS

CL and HM gave substantial contributions to the conception and design of the work. They approved the final version to be published. For all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved by them and declare to be accountable. Interpretation of data and drafting of the manuscript was done conjointly by them, both bringing in important intellectual content. CL was mainly responsible for data collection and analysis.

FUNDING

This research was supported by the German Research Foundation, DFG-Priority Program 1772, MU 1374/5-1.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 03 May 2018
doi: 10.3389/fpsyg.2018.00602

Cognitive—Motor Interference in an Ecologically Valid Street Crossing Scenario

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Laboratory-based research revealed that gait involves higher cognitive processes, leading to performance impairments when executed with a concurrent loading task. Deficits are especially pronounced in older adults. Theoretical approaches like the multiple resource model highlight the role of task similarity and associated attention distribution problems. It has been shown that in cases where these distribution problems are perceived relevant to participant's risk of falls, older adults prioritize gait and posture over the concurrent loading task. Here we investigate whether findings on task similarity and task prioritization can be transferred to an ecologically valid scenario. Sixty-three younger adults (20–30 years of age) and 61 older adults (65–75 years of age) participated in a virtual street crossing simulation. The participants' task was to identify suitable gaps that would allow them to cross a simulated two way street safely. Therefore, participants walked on a manual treadmill that transferred their forward motion to forward displacements in a virtual city. The task was presented as a single task (crossing only) and as a multitask. In the multitask condition participants were asked, among others, to type in three digit numbers that were presented either visually or auditorily. We found that for both age groups, street crossing as well as typing performance suffered under multitasking conditions. Impairments were especially pronounced for older adults (e.g., longer crossing initiation phase, more missed opportunities). However, younger and older adults did not differ in the speed and success rate of crossing. Further, deficits were stronger in the visual compared to the auditory task modality for most parameters. Our findings conform to earlier studies that found an age-related decline in multitasking performance in less realistic scenarios. However, task similarity effects were inconsistent and question the validity of the multiple resource model within ecologically valid scenarios.

Keywords: multitasking, dual-tasking, aging, walking, cognitive-motor interference, ecological validity, virtual reality, street crossing

OPEN ACCESS

Edited by:
Karen Zentgraf, Goethe University Frankfurt, Germany

Reviewed by:
André Klostermann, Universität Bern, Switzerland
Herbert Heuer, Leibniz Research Centre for Working Environment and Human Factors (LG), Germany

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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: 03 February 2018
Accepted: 10 April 2018
Published: 03 May 2018

Citation:
Janouch C, Drescher U, Wechsler K, Haeger M, Bock O and Voelcker-Rehage C (2018) Cognitive—Motor Interference in an Ecologically Valid Street Crossing Scenario. Front. Psychol. 9:602. doi: 10.3389/fpsyg.2018.00602

INTRODUCTION

Many daily activities require us to manage sensory-motor tasks while we simultaneously engage in cognitive tasks. One prominent example is pedestrian mobility, such as walking down a sidewalk while avoiding a collision with another pedestrian, walking while screening items in a shop window, or crossing a non-signalized street while paying attention to relevant traffic information. These activities become even more complex with the advent of portable technologies such as smartphones or music players. In June 2013 the Pedestrian Survey Infographic published, that from over 1,000 American respondents three out of five (60%) 18–65 year olds stated to use smartphones while crossing a street, even though this was considered as dangerous by 70% of these respondents (Liberty Mutual Insurance, 2013).

Standardized laboratory paradigms have provided evidence that sensory-motor performance decreases under dual-task conditions, and that this decrease is especially pronounced in older adults (Kray and Lindenberger, 2000; Verhaeghen et al., 2003). This has been often explained by sensory-motor and cognitive declines within the aging process (Baltes and Lindenberger, 1997; Li and Lindenberger, 2002). Performance decrements in dual-task situations have even been observed with tasks that are considered to be highly automated, like gait. It has therefore been argued that even gait requires cognitive control and higher-level resources (Hausdorff et al., 2005; Yogev-Seligmann et al., 2008). Especially in older adults, gait seems to place high attentional demands and requires more cognitive resources (Lindenberger et al., 2000; Woollacott and Shumway-Cook, 2002; Hausdorff et al., 2008) which leads to greater dual-task decrements in this age group (Al-Yahya et al., 2011).

Performance decrements in dual-task situations have been interpreted in light of several theoretical positions, such as capacity models of attention (Kahneman, 1973) or multiple resource models (Wickens, 2002). In both types of models, two or more tasks compete for common resources, either within a limited attentional resource pool (Kahneman, 1973) or within multiple resource pools (Wickens, 2002). In the latter case, pools are thought to be devoted to different stimulus modalities, signal codes, processing stages, and response channels (Wickens and McCarley, 2007). Both theoretical approaches share the idea that performance deteriorates when the competing tasks are so complex that their combined resource demand exceeds the available resource capacity. The multiple-resource model additionally posits that the tasks must be similar enough in order to compete for the same resource. The determinants of dual-task decrements therefore are task complexity and—in case of the multiple-resource model—task similarity.

Several studies provided evidence for the role of task similarities. They documented interference between tasks that share sensory modalities, processing levels or information channels (Allport et al., 1972; Isreal et al., 1980; Duncan et al., 1997; Talsma et al., 2006). In a street crossing context, such interference could emerge when two tasks require to simultaneously process similar visual signals. This is the case, e.g., when we look for a suitable gap in traffic and concurrently read walking directions on a mobile phone. In contrast, looking for gaps while listening to walking directions over headphones should cause less interference.

So far, most available knowledge about dual-task performance came from traditional laboratory-based research that offers a high controllability and standardization, but lacks ecological validity. Even if real walking is required, tasks are often executed within a laboratory surrounding and most of the applied loading tasks are rather abstract like verbal fluency or arithmetic subtraction tasks. For example, participants were asked to memorize word lists while walking (walk as accurately and quickly as possible on two narrow tracks with different path complexity/avoid obstacles) (Lindenberger et al., 2000; Li et al., 2001). The results revealed diminished performance when the tasks were performed concurrently. Age-related differences were more pronounced in the memory task than in the walking task. This result was discussed as older adults prioritizing walking over memorizing to protect themselves from falls, a view known as "posture first hypothesis" (Shumway-Cook and Woollacott, 2000; Schaefer and Schumacher, 2011; cf. Li et al., 2012 for discussion of mixed results).

Everyday life typically differs from traditional laboratory paradigms in that behavior is uninstructed and volitional, with varying and often unpredictable stimuli and with a wider range of possible and purposeful responses. Little is known about the transferability of laboratory outcomes to more realistic settings. Available literature documents marked differences between laboratory and realistic behavior with respect to gait (Bock and Beurskens (2010), manual grasping (Bock and Züll, 2013) and cognitive performance (Verhaeghen et al., 1993). In a systematic review on dual-task training effects in older adults, Wollesen and Voelcker-Rehage (2014) found heterogeneous results regarding the transferability of training effects to everyday situations. Consequently, several authors cautioned against generalizing laboratory results to real life (Chaytor and Schmitter-Edgecombe, 2003; Li et al., 2005) and questioned the extent to which especially age-related decays apply on everyday-like behavior (Verhaeghen et al., 2012).

Given the above considerations, it seems desirable to expand dual-task research by using more ecologically valid paradigms, without giving up the advantages of a laboratory setting such as controllability and standardization. A promising approach to do so can be seen in virtual reality (VR) settings (Lopez Maite et al., 2016) which can provide an everyday-like, controllable and safe surrounding that can be adapted to the need of the experimenter. Thus, a realistic walking task (e.g., walking down or crossing a street) can be combined with a realistic loading task (e.g., watching for vehicles or using a smartphone) while ambient stimuli are controlled for and relevant measures are extracted. Indeed, several VR pedestrian street crossing studies have been conducted recently (Dommes et al., 2014; Schwebel et al., 2014; Morrongiello and Corbett, 2015). However, most of these studies did not address multitasking (Dommes et al., 2014; Schwebel et al., 2014; Morrongiello and Corbett, 2015) and those which did rather focused on children and young adults than older adults (Chaddock et al., 2011, 2012; Byington and Schwebel, 2013; Gaspar et al., 2014; Tapiro et al., 2016) or used only a single loading task throughout the whole experimental block or session (Neider et al., 2011). For example, Neider et al. (2011) confirmed that dual-task crossing performance deteriorates in old age, but did not evaluate performance changes of the cognitive loading task (cell phone conversation) to control for interaction effects or possible prioritization strategies.

The present study aims to overcome the mentioned limitations by combining a VR street crossing task with a realistic loading task. We posit that the ecological validity of our approach exceeds that of earlier approaches. Specifically, loading tasks are administered either through the visual or the auditory modality, in order to scrutinize the validity of the multiple resource model (Wickens, 2002) for ecologically valid settings. We hypothesized that street crossing requires visual resources and therefore will interfere with visually presented loading tasks more than with auditorily presented loading tasks, particularly in older persons. In accordance with the posture first hypothesis (Lindenberger et al., 2000; Li et al., 2001; Schaefer and Schumacher, 2011), we expected that age-related deficits will be less pronounced for walking than for loading task performance, even in an ecologically valid setting.

METHODS

Participants

The study was conducted within the DFG (German Research Foundation) Priority Program SPP 1772 "Multitasking," In total, 134 healthy men and women between 20 and 30 ($n = 69$) and 65 and 75 ($n = 65$) years of age who actively participated in traffic as drivers as well as pedestrians were recruited. Younger participants were recruited via mailing lists from the student pool of the Chemnitz University of Technology (Germany) and the German Sport University Cologne. Older adults were acquired via local newspaper advertising and (only in Chemnitz) further via the participant pool of the Cognition, Brain, and Movement Lab of Chemnitz University of Technology. About half of the young and old participants were recruited and tested in Chemnitz and the other half in Cologne. Both locations used standardized and indentical set ups, test designs and instructions as well as identical hardware and software.

Interested persons were screened in an initial telephone interview for the following exclusion criteria: (a) age range violations, (b) former or current health impairments (heart attacks, brain injuries, strokes; motor impairments that inhibit the participant to continuously walk for 30 min, eye diseases or current relevant injuries), (c) obesity (Body Mass Index, BMI > 30), and (d) driving irregularity (driving a car less than once a week). Further exclusion tests were performed on participant's first laboratory test session (cf. below). No person had to be excluded based on these tests. Before testing began, participants obtained medical clearance from their local physician and signed an informed consent statement to our study. This experiment was part of a larger project in which the same participants were additionally given a car-driving test (reported in another contribution to this issue) and a cardiovascular fitness test. The project was approved by the Ethics Committee of the German Sport University, Cologne.

Six participants dropped out over the study time without giving reasons, three had to be excluded because of simulator sickness, and one participant left the study for personal reasons. The remaining 124 participants were subdivided with respect to age into 61 older adults (OA) with a mean age of 69.97 ($SD = 2.96$) years [females: $n = 22$; BMI = 25.09 ($SD = 2.44$); MMSE = 29.15 ($SD = 0.85$)] and 63 young adults (YA) with a mean age of 23.17 ($SD = 2.83$) years [females: $n = 40$; BMI = 22.04 ($SD = 2.30$); MMSE = 29.67 ($SD = 0.62$)]. OA received 15 € per session as monetary compensation (60 € in total) and YA received course credits. Further, all participants received an individual report of their cardiovascular fitness test as compensation.

Laboratory Screening

Normal hearing was assessed by the Freiburg speech intelligibility test (Freiburger Sprachverständlichkeitstest) with a set cutoff word recognition rate of 50 %. Normal vision was assessed by the Freiburg Visual Acuity Test (FrACT; version 3.9.0) with a cutoff score of 20/60 since driving is presumed to be safe above that score (Keeffe et al., 2002). Lack of visual-field deficits was confirmed by the online version of the Damato Multifixation Campimeter (Damato and Groenewald, 2003). All participants who used visual and hearing aids in their daily life did so in testing as well. Normal overall cognition was assessed by the Mini-Mental State Examination (Folstein et al., 1975) with a cutoff score of 27/30. Finally, the Edinburgh Handedness Inventory (Oldfield, 1971) was used to determine hand dominance. Five participants were left handed, one was ambidextrous but preferred the right hand for typing, and all others were right handed.

Apparatus and Setup

Hardware for the street crossing task consisted of a non-motorized treadmill (DRAX, Speedfit 1000c, Vibrafit®, Solms) and three 46″ TV flat screens that featured a 195 degree horizontal field of view. Treadmill speed was registered opto-electronically, and was synchronized with a first person perspective view of a 3D world. Thus, as participants walked at their own pace, sped up, and slowed down, their viewpoint in the visual 3D world moved accordingly. To reduce physical exertion, participants were asked not to run. For safety reasons, each participant was equipped with a drop guard and asked to keep the non-dominant hand on the treadmill's handrail for the entire test duration.

Headphones (Shark Zone H10 Gaming Headset, Sharkoon Technologies GmbH, Linden, Germany) were used to deliver auditory stimuli and a microphone to register verbal responses. A keypad with 2 × 3 digits was attached within easy reach of the participants' dominant/preferred hand to register manual typing responses.

Software consisted of a modified, commercially available driving simulator (Carnetsoft®, version 8.0 Groningen, NL) that was adapted to the needs of a street crossing task: it displayed the 3D model of a city street from a first person perspective (see section Street Crossing Task).

Figure 1 illustrates the set up and displays the modeled city street.

Street Crossing Task

The street crossing task was designed similarly to a study by Neider et al. (2010), in which the participant's task was to safely cross a street presented in virtual reality. To do so, they had to detect suitable gaps between the oncoming vehicles. In our scenario, the street consisted of one three-meter wide lane in each direction and was flanked by typical downtown buildings. Vehicles traveled along both lanes at 50 km/h, which is the legal driving speed in German towns. At the onset of each trial, participants walked 15 m through a virtual back alley to reach the curb of the street, stopped, watched for a suitable intervehicle gap and then crossed. Intervehicle gaps increased during each trial according to the sequence 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6 s, and this sequence was repeated if participants did not cross the street yet. Cars on the far lane reached the crossing area one second later than those on the near lane. Pilot work yielded that this traffic pattern allows safe crossing even for older participants. Far lane traffic was implemented to detect possible behavioral anomalies during the crossing process (e.g., stopping in the middle of the street to let pass the traffic on the far lane before continuing crossing). However, as no such anomalies occurred and analyses of near and far lane provided equally results, only near lane analyses will be reported. A crossing trial was completed when participants reached the opposite walkway, when they caused an accident or when 80 s elapsed.

Loading Task

We used two realistic loading tasks that resembled rehearsal of a shopping list (shopping task) and smartphone usage (typing task). Each given loading task was presented repeatedly from trial onset until trial end to ensure that the crossing task and the loading task could not be dealt with sequentially. Loading tasks were presented visually on some, and auditorily on other trials.

In the *shopping task*, grocery products were sequentially presented either visually on billboards across the street or auditorily through headphones. In the *typing task*, three-digit numbers were sequentially presented either on the billboards (for 4 s each) or through headphones, for about 1.7 s each. Participants reacted by depressing, with their preferred hand, the corresponding numbers on a keypad that was attached to the treadmill handrail. Task type (shopping, typing) and task modality (visually or auditorily) varied quasi-randomly between trials, with the constraint that each type*modality combination was presented a total of ten times. To limit the complexity of the present paper, we decided to focus our analyses on the typing task. However, it is important to note that this task was not administered alone but rather intermixed with the shopping task, to mimic the diversity of everyday multitasking. Possible switching costs, resulting from such a loading task intermix will be discussed in a car driving simulator study by Wechsler et al. (under review).

The simulation offered three task conditions. In the control condition "single-task crossing (STcross)," participants walked on the treadmill and crossed the virtual street without loading tasks. In the condition "single-task loading," participants stood still on the treadmill while the virtual reality display advanced automatically and the loading tasks were displayed sequentially. In this condition, each type*modality combination [typing auditory (STtype_aud), typing visual (STtype_vis), shopping auditory (STshop_aud) and shopping visual (STshop_vis)] was presented with a total of 10 trials. In the condition "multitask," participants walked on the treadmill and crossed the virtual street while concurrently engaged in a loading task (MTtype). Again, there where 10 trials of each type*modality combination [auditory typing task (MTtype_aud), visual typing task (MTtype_vis), auditory shopping task (MTshop_aud), and visual shopping task (MTshop_vis)].

Ten control trials of STCross were randomly intermixed with ten trials each of MTtype_aud, MTtype_vis, MTshop_aud, and MTshop_vis. The total of 50 trials was presented in blocks of ten trials each that were characterized as active blocks in which participants had to actually walk on the treadmill. These active blocks alternated with passive blocks of ten single-task loading trials each in which the participants stood still on the treadmill. The latter blocks were formed by intermixing ten trial each of STtype_aud, STtype_vis, STshop_aud, and STshop_vis. The alternation of active and passive blocks was introduced to avoid fatigue. All participants received the same sequence of trials, which took about 40 min.

Procedure

All data were collected in four sessions of about 2 h each, scheduled one to seven days apart. The first session included

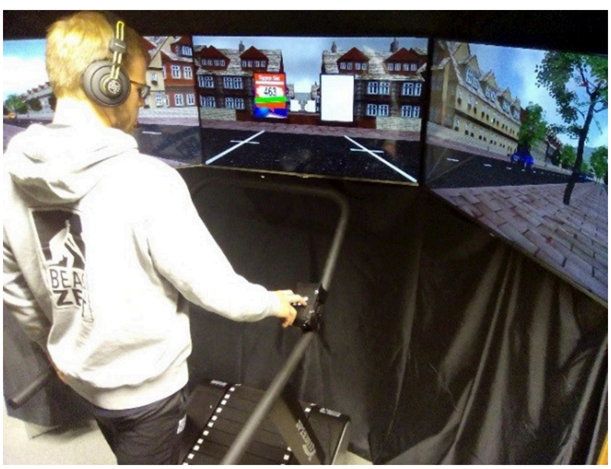

FIGURE 1 | Street crossing simulator set up.

TABLE 1 | Means (M) and Standard Deviations (SD) of crossing parameters during single-task crossing (STCross), multitask typing visually (MTtype_vis) and multitask typing auditorily (MTtype_aud).

	STCross M (*SD*)		MTtype_vis M (*SD*)		MTtype_aud M (*SD*)	
	YA	OA	YA	OA	YA	OA
Stay Time	6.29 (0.97)	6.48 (0.99)	7.26 (4.19)	9.51 (5.99)	6.27 (0.91)	6.41 (1.01)
Back-alley Speed (km/h)	3.94 (0.61)	3.75 (0.59)	3.80 (0.60)	3.51 (0.61)	3.72 (0.61)	3.37 (0.62)
Crossing Speed (km/h)	6.37 (0.97)	6.70 (1.03)	6.26 (0.94)	6.14 (1.02)	6.30 (1.02)	6.33 (1.08)
Crossing Failure (%)	10.63 (16.74)	9.51 (14.19)	16.35 (19.12)	21.31 (21.64)	11.43 (14.69)	15.08 (16.29)
Gap (#)	4.87 (1.32)	5.17 (1.30)	5.11 (1.24)	5.98 (1.53)	5.10 (1.33)	5.98 (1.39)

a screening (see above) and a familiarization phase in which participants walked on the treadmill. This phase ended when participants and experimenter considered starting, walking and stopping on the treadmill to be smooth and effortless, which took about 10–15 min for YA, and 15–20 min for OA. Afterwards, participants received one practice trial each for STtype_vis, STtype_aud, and STcross. MTtype was not practiced.

Street crossing performance was registered in one of the remaining three test sessions, depending on participant's test order randomization. It was assured that the street crossing experiment was never scheduled on the same day as the cardiovascular fitness test, to avoid fatigue.

Data Reduction

The following performance measures were calculated.

Back-alley Speed (km/h): Mean velocity of walking toward the curb. Triggers were set at trial onset, and when participants stopped at the curb.

Stay Time (s): Length of time that participants stood still at the curb while watching traffic. Time triggers were set when treadmill pace dropped to 0 m/s and when treadmill pace exceeded 0 m/s thereafter.

Crossing Speed (km/h): Mean velocity of crossing the street. Triggers were set when participants left the curb to cross (treadmill pace > 0 m/s) and when they reached the opposite curb.

Crossing Failures: Percentage of unsuccessful trials, as a result of timeouts (i.e., participant did not complete street crossing within 80 s) or experienced a collision (i.e., participant was hit by a car).

Gap Number: Serial order of the gap selected for crossing.

Typing Accuracy (%): Percentage of trials on which all three digits were typed correctly.

Typing Reaction Time (*ms*): Interval from stimulus onset until typing the first digit.

Multitasking Effects, MTE: Relative performance change under multitask conditions, with negative values indicating poorer performance (cf. Kelly et al., 2010; Plummer and Eskes, 2015). For *Back-alley Speed, Crossing Speed,* and *Typing Accuracy* MTE was calculated as

$$MTE = \frac{\text{Multitask performance} - \text{Single task performance}}{\text{Single task performacne}} \, x\, 100\% \quad (1)$$

while for Stay Time, Crossing Failure, Gap Number, and Typing Reaction Time it was calculated as

$$MTE = -\left(\frac{\text{Multitask performance} - \text{Single task performance}}{\text{Single task performancne}} \, x\, 100\%\right) \quad (2)$$

Statistical Analyses

Outliers were eliminated by applying the ±3.29 *SD* criterion (Tabachnick and Fidell, 2001), separately for each participant and task. Data were then averaged across repetitions if at least seven repetitions remained, which was the case for all 124 participants.

Each street crossing parameter was submitted to an analysis of variance (ANOVA) with Age (OA, YA) as between-subject factor and Condition (STcross, MTtype_aud, MTtype_vis) as within-subject factor. Typing parameters were submitted to an ANOVA with Age (OA, YA) as between-subject factor and Condition (STtype, MTtype) and Task Modality (visual, auditory) as within-subject factors.

Each MTE score was tested against zero with one-sample *t*-tests in case of normal distributions, and Wilcoxon Signed Rank tests otherwise. Further, MTE scores were submitted to an ANOVA with Age (OA,YA) as between-subject factor and Parameter Type (Stay Time, Walking Speed, Crossing Speed, Failures, Gap, Typing Accuracy and Typing Reaction Time) as well as Task Modality (visual, auditory) as within-subject factors.

Effect sizes are reported as partial eta squares. Homogeneity of variances was determined by Mauchly-tests and, if the sphericity assumption was violated, Greenhouse-Geisser adjustments were applied. When omnibus ANOVA was significant, Bonferroni *post-hoc* tests were conducted. All statistical analyses were conducted with SPSS for Windows, version 25 (IBM Corp., Armonk, NY, USA).

RESULTS

Crossing Task

Table 1 and **Figure 2** show descriptive data on each street crossing parameter and **Table 2** pertinent ANOVA results.

Back-alley Speed was significantly slower in OA than YA and differed between conditions (**Figure 2A**). It was significantly slower in the MTtype conditions compared to the STCross condition but also differed significantly between both MTtype

TABLE 2 | ANOVA results for street crossing parameters.

	df (Error)	*F*	Sig	η_p^2
BACK-ALLEY SPEED				
Condition	1.672 (203.929)	95.064	<0.001**	0.438
Age	1 (122)	7.038	0.009**	0.055
Condition × Age	1.672 (203.929)	5.930	0.005**	0.046
STAY TIME				
Condition	1.009 (123.112)	18.344	<0.001**	0.131
Age	1 (122)	6.937	0.010*	0.054
Condition × Age	1.01 (123.112)	4.855	0.029*	0.038
CROSSING SPEED				
Condition	2 (244)	40.003	<0.001**	0.247
Age	1 (122)	0.220	0.640	0.002
Condition × Age	2 (244)	17.677	<0.001**	0.247
CROSSING FAILURE				
Condition	1.895 (231.246)	18.423	<0.001**	0.131
Age	1 (122)	0.915	0.341	0.007
Condition × Age	1.895 (231.246)	2.407	0.095	0.019
GAP				
Condition	2 (244)	33.970	<0.001**	0.218
Age	1 (122)	9.228	0.003**	0.070
Condition × Age	2 (244)	11.609	<0.001**	0.087

$^*p < 0.05$; $^{**}p < 0.01$.

conditions (slowest in MTtype_aud followed by MTtype_vis and fastest in STCross), especially in OA (significant age × condition interaction). Pairwise *post-hoc* comparisons revealed that age differences only emerged in the MTtype conditions (MTtype_vis: $p = 0.007$; MTtype_aud: $p = 0.002$), but not in STCross ($p = 0.066$).

Stay time was significantly longer in OA than YA and different between conditions (**Figure 2B**). It was significant longer in MTtype_vis compared to MTtype_aud and compared to STCross (always, $p < 0.001$), particularly so in older persons as shown by a significant age by condition interaction. However, *post-hoc* tests revealed significant age differences in MTtype_vis only ($p = 0.016$).

Crossing Speed did not differ as a function of age, but again differed between conditions (**Figure 2C**). Also the age by condition interaction was significant, indicating that only for older adults *Crossing Speed* was significantly affected by condition. OA were significantly slower in both MTtype conditions compared to STcross, but this time with the slowest *Crossing Speed* in MTtype_vis that was also significantly slower compared to the MTtype_aud condition ($p = 0.001$).

Crossing Failure revealed a significant condition effect only (**Figure 2D**). *Post-hoc* comparisons revealed that this effect was driven by MTtype_vis for which *Crossing Failure* was significantly higher compared to STCross ($p < 0.001$) as well as to MTtype_aud ($p < 0.001$).

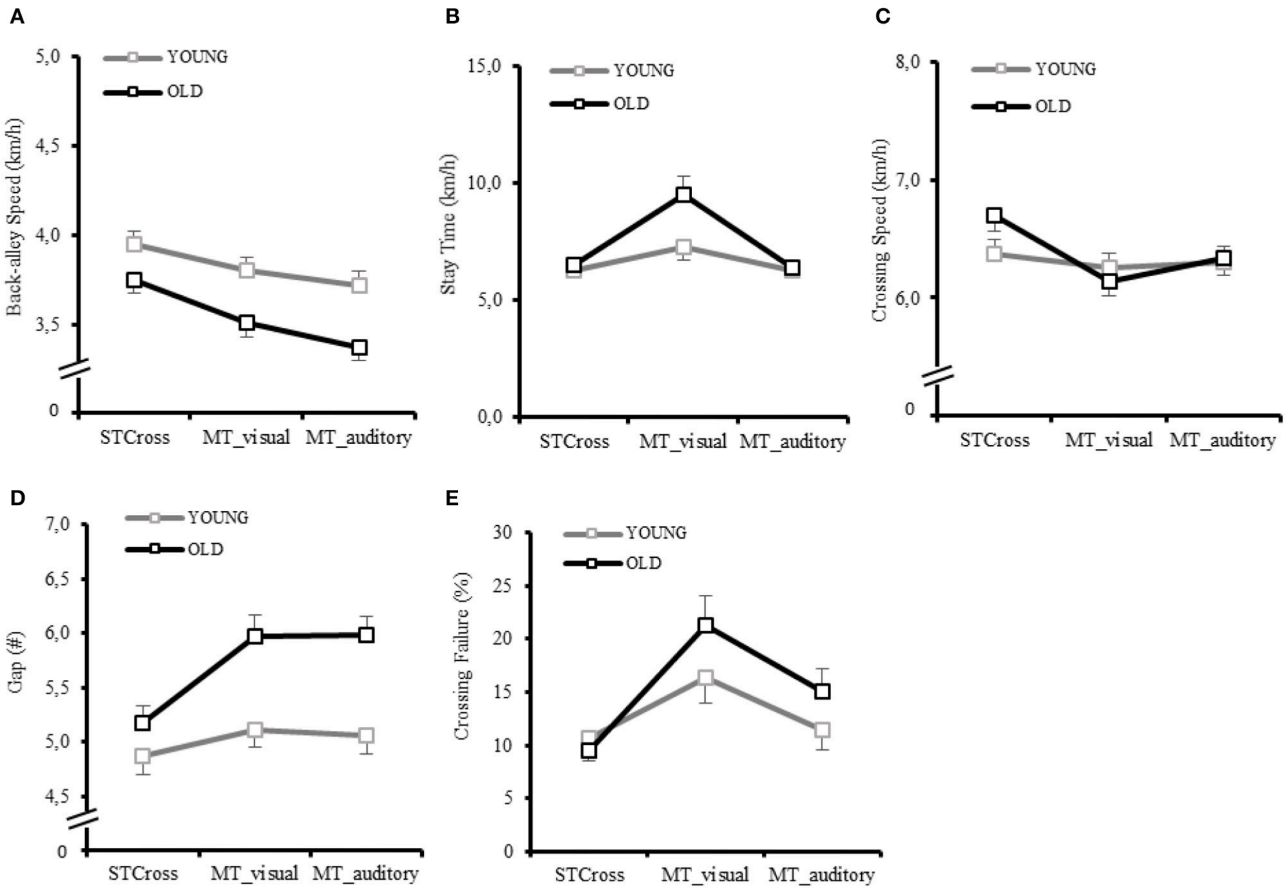

FIGURE 2 | Condition differences between single-task crossing (STCross), multitask typing visually (MTtype_vis) and multitask typing auditorily (MTtype_aud), grouped by age (M and SE) for **(A)** Back-alley Speed; **(B)** Stay Time; **(C)** Crossing Speed; **(D)** Gap Number; **(E)** Crossing Failures.

TABLE 3 | Means (M) and Standard Deviations (SD) of typing parameters for younger (YA) and older adults (OA).

	STTyping_visual M (*SD*)		**MT_visual M (*SD*)**		**STTyping_auditory M (*SD*)**		**MT_auditory M (*SD*)**	
	YA	**OA**	**YA**	**OA**	**YA**	**OA**	**YA**	**OA**
Accuracy in %	95.70 (1.17)	95.10 (1.36)	95.80 (1.13)	94.11 (3,66)	96.58 (3.51)	96.74 (7.80)	92.73 (5.05)	89.61 (8.31)
Reaction Time (s)	1.44 (0.19)	1.73 (0.18)	1.62 (0.24)	1.94 (0.22)	1.75 (0.25)	1.57 (0.21)	1.78 (0.23)	1.72 (0.21)

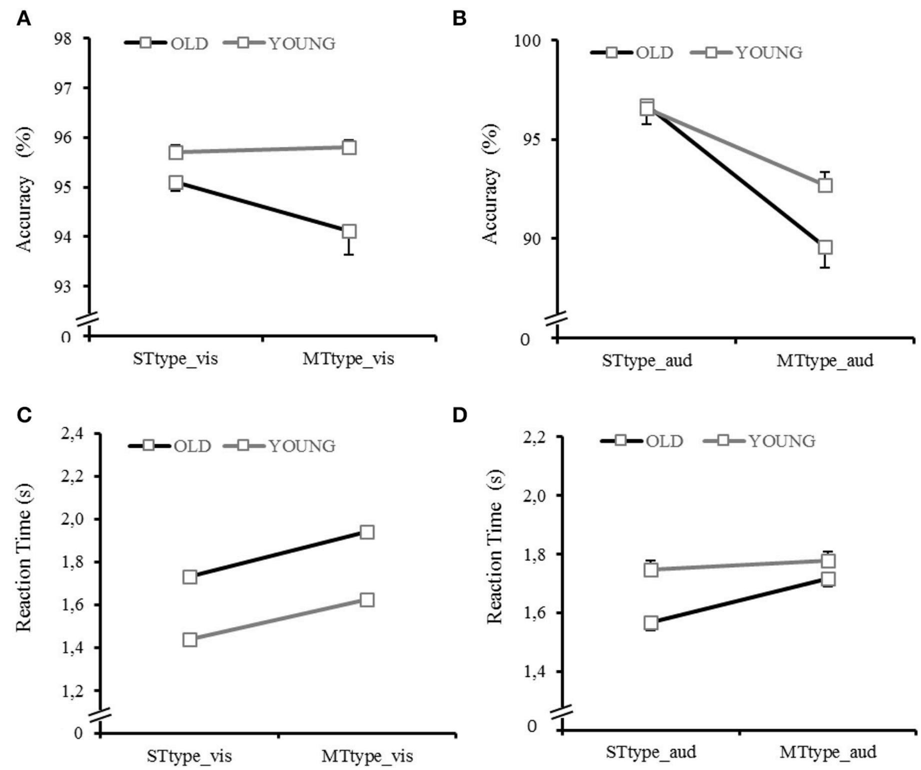

FIGURE 3 | Condition differences between single-task typing visual (STtype_vis) and multitask typing visual (MTtype_vis) and between single task typing auditory (STtype_aud) and multitask typing auditory (MTtype_aud) for **(A)** accuracy visual; **(B)** accuracy auditory; **(C)** reaction time visual; **(D)** reaction time auditory.

TABLE 4 | ANOVA results for typing parameters.

	df	*F*	Sig	η_p^2
Accuracy				
Age	1 (122)	8.894	0.004**	0.067
Condition	1 (122)	51.217	<0.001**	0.296
Condition × Age	1 (122)	6.937	<0.001**	0.054
Task Modality	1 (122)	7.992	0.005**	0.061
Task Modality × Age	1 (122)	0.143	0.706	0.001
Condition × Task Modality	1 (122)	36.702	<0.001**	0.231
Condition × Age × Task Modality	1 (122)	1.728	0.191	0.014
REACTION TIME				
Age	1 (122)	9.401	0.003**	0.072
Condition	1 (122)	112.852	<0.001**	0.481
Condition × Age	1 (122)	6.912	0.010*	0.054
Task Modality	1 (122)	1.094	0.298	0.009
Task Modality × Age	1 (122)	145.077	<0.001**	0.543
Condition × Task Modality	1 (122)	31.572	<0.001**	0.206
Condition × Age × Task Modality	1 (122)	6.283	0.014*	0.049

$^*p < 0.05$; $^{**}p < 0.01$.

OA selected later *Gaps* than YA (significant effect of Age), and gap selection was significant earlier within STcross compared to both MTtype conditions (significant condition effect; both $p < 0.001$) (**Figure 2E**). As indicated by the age by condition interaction, this condition effect was only driven by OA. Pairwise *post-hoc* comparisons revealed significant age differences in MTtype_vis ($p = 0.001$) and MTtype_aud ($p < 0.001$).

Typing Task

Table 3 and **Figure 3** show descriptive data on all typing task parameters and **Table 4** pertinent ANOVA results.

Accuracy scores for typing were significantly lower in OA than to YA, significantly lower in MTtype conditions than to STtype conditions and significantly lower in the auditory than the visual task modality (**Figures 3A,B**). The condition by age interaction and corresponding *post-hoc* tests revealed, that age differences only occurred in the MT conditions ($p < 0.001$). Differences between STtype and MTtype conditions occurred for the auditory task modality ($p < 0.001$), while task modality differences occurred within both conditions (significant condition × task modality interaction).

Reaction Time was significantly longer for OA than YA (age effect) and longer in MTtype conditions than STtype conditions (condition effect) (**Figures 3C,D**). This was particularly true for OA as shown by the age × condition interaction. Pairwise comparisons revealed, that age differences only occurred in the MTtype conditions ($p < 0.001$) but within both task modalities (auditory: $p = 0.001$; visual $p < 0.001$; significant age × task modality interaction).

Condition differences were found within both task modalities but task modality differences were only present in STtype condition (significant condition × task modality interaction). Pairwise comparisons for the condition × modality × age interaction revealed that within the visual task modality, age differences were present in the single task ($p < 0.001$) as well as the multitasks (always $p < 0.001$). Within the auditory task modality, age differences were only present in the STtype condition ($p < 0.001$).

Multitasking Effects

Table 5 shows MTE scores for crossing as well as typing parameters, and their differences from zero. Within the visual task modality, significant non-zero MTE scores emerged for both age groups in all street crossing parameters and in *Reaction Time*. Within the auditory task modality, significant non-zero MTE scores in both age groups were only yielded for *Walking Speed*, *Gap,* and *Accuracy*, while significant non-zero MTE for *Crossing Speed*, *Crossing Failure,* and *Reaction Time* were only found in OA. These data did not support a consistent relationship between multitasking deficits and task modality.

Prioritization: Street Crossing-Related MTE vs. Typing-Related MTE

The ANOVA results for MTE are depicted in **Table 6**, and the pertinent *post-hoc* comparisons are summarized in **Table 7**. MTE differed significantly between street crossing-related and typing-related parameters. OA were more likely to produce significant differences between street crossing- and typing-related MTE compared to YA. Further, in the visual task modality significantly higher MTE occurred more frequently for the street crossing-related parameters than for the typing-related ones, especially in OA. This was contrary to findings in the auditory task modality, where significantly higher MTE were produced more frequently in the typing task. However, the direction of those differences was not consistent overall, for a given age group or for a given modality.

These data argued against an overall or an age-dependent prioritization of the street-crossing or the typing task. To emphasize this lack of an overall prioritization strategy, we plotted the Means of significant street crossing-related vs. typing-related MTE differences, grouped by age (see **Figure 4**).

TABLE 5 | Means (M) and Standard Deviations (SD) of multitasking effects within the visual task modality (MTE visual) and within the auditory task modality (MTE auditory), and their difference from zero.

	MTE visual		MTE auditory	
	YA	OA	YA	OA
	M (*SD*)	M (*SD*)	M (*SD*)	M (*SD*)
CROSSING PARAMETERS				
Stay Time (s)	−25.91 (68.91)**	−86.94 (191.59)**	−0.79 (6.15)	−1.01 (7.04)
Back-alley Speed (km/h)	−3.56 (5.29)**	−6.28 (8.45)**	−5.69 (5.08)**	−10.05 (8.13)**
Crossing Speed (km/h)	−1.61 (4.94)*	−8.10 (8.36)**	−0.95 (5.66)	−5.48 (6.57)**
Crossing Failure (%)	−5.71 (16.24)**	−11.80 (19.79)**	−7.94 (14.29)	−5.57 (16.38)*
Gap (#)	−6.93 (15.65)**	−17.59 (24.93)**	−5.12 (15.39)*	−19.16 (26.91)**
TYPING PARAMETERS				
Accuracy	0.12 (1.79)	−1.03 (3.87)	−3.69 (5.28)**	−7.41 (6.36)**
Reaction time	−13.18 (11.52)**	−12.74 (13.11)**	−2.60 (11.35)	−10.44 (12.19)**

*$p < 0.05$; **$p < 0.01$.

TABLE 6 | ANOVA results for multitasking effects.

	df (Error)	*F*	Sig	η_p^2
Age	1 (122)	9.566	0.002**	0.073
Parameter Type	6 (154.025)	19.637	<0.001**	0.139
Parameter Type × Age	6 (154.025)	5.296	0.016*	0.042
Task Modality	1 (122)	24.151	<0.001**	0.165
Task Modality × Age	1 (122)	0.068	0.068	0.027
Parameter Type × Task Modality	6 (132.331)	18.744	<0.001**	0.133
Parameter Type × Age × Task Modality	6 (132.331)	6.180	0.012*	0.048

*$p < 0.05$; **$p < 0.01$.

DISCUSSION

The aim of this study was to expand available dual-task research by using an ecologically valid task, street crossing in virtual reality, and by including realistic loading tasks and stimulus modalities. The loading task was delivered via two different task modalities (visual vs. auditory) to further provide a theoretical contribution toward the multiple resource theory and Mulittasking Effects were considered to identify possible general prioritization strategies.

We expected to confirm that even in our ecologically valid scenario the costs of multitasking increase in older age and that this increase is more pronounced in the loading tasks as compared to the street crossing task, in accordance with the posture-first hypothesis (Lindenberger et al., 2000; Li et al., 2001; Schäfer et al., 2006). Further we expected that this increase is more pronounced in the visual than the auditory task modality, in accordance with the multiple-resource model (Wickens, 2002).

In accordance with our first expectation, we found that street crossing as well as typing performance suffered under multitasking conditions, and that impairments were more pronounced in older adults. When multitasking, older adults slowed down more than young ones when approaching the curb and when crossing the street, waited longer at the curb, and therefore selected a later gap for crossing. This is in line with previous street crossing studies which also found longer approach durations (Banducci et al., 2016), longer preparation durations (Neider et al., 2010, 2011; Chaddock et al., 2011, 2012; Byington and Schwebel, 2013; Gaspar et al., 2014; Banducci et al., 2016) and more missed crossing opportunities (Stavrinos et al., 2011; Byington and Schwebel, 2013). Our findings are also in line with traditional laboratory studies, which found stronger

TABLE 7 | *Post-hoc* comparisons between street crossing-related (rows) and typing-related (columns) multitasking effects, separately for each age group (YA; OA) and task modality.

MTE (%)	Visual task modality				Auditory task modality			
	YA	OA	YA	OA	YA	OA	YA	OA
	Reaction Time	Reaction Time	Accuracy	Accuracy	Reaction Time	Reaction Time	Accuracy	Accuracy
Back-alley Speed	_<0.001**_	_<0.001**_	__0.003**__	__<0.001**__	__<0.001**__	_<0.001**_	__<0.001**__	__<0.001**__
Stay Time		__0.002**__		__<0.001**__		_0.041*_	_<0.001**_	_<0.001**_
Crossing Speed	_<0.001**_	_<0.001**_		__<0.001**__		_0.001**_	_<0.001**_	_<0.001**_
Crossing Failure				__<0.001**__				
Gap				__<0.001**__				__0.002**__

*$p < 0.05$; **$p < 0.01$. Bold, Street crossing MTE > Typing MTE; Italic, Typing MTE > Street crossing MTE.

effects of multitasking on gait speed for older than young persons (Lindenberger et al., 2000; Hausdorff et al., 2008).

The age-related decrement of multitasking abilities manifested not only in four of our five street-crossing parameters, but also in both loading-task parameters. This conforms earlier findings about differential effects of age on loading-task performance (Lindenberger et al., 2000; Li et al., 2012), and extends them to an ecologically valid scenario.

Surprisingly, we did not find age-related decrements in *Crossing Speed*, even though a reduced walking speed in OA compared to YA under dual-task conditions has been reported in dual-task gait studies before (Lindenberger et al., 2000; Hausdorff et al., 2008). In contrast, Neider et al. (2011) reported even smaller crossing durations (i.e., faster crossing speeds) in OA as compared to YA and interpreted this finding as a greater perceived urge in OA to avoid (virtual) collisions. In our study, both age groups crossed the street very quickly (around 6 km/h) which means that especially OA accelerated their regular walking speed (4.6–4.9 km/h; Samson et al., 2001) and invested more motor (and cognitive) resources in order to complete the crossing as fast as possible. Especially in a demanding multitasking situation, this additional invest of resources might exceed the limits of their processing capacity.

In accordance with our second expectation, multitasking had more pronounced effects on the loading tasks than on the street-crossing task, but this was the case for only about half of the age × modality × parameter combinations (cf. **Table 5**). For the other half, multitasking had more pronounced effects on the street-crossing task. This heterogeneity persists even when only the two crossing parameters with the closest link to posture and gait are considered, namely, *Back-alley Speed* and *Crossing Speed*. From this we conclude that the posture-first hypotheis may not be applicable unconditionally (Li et al., 2012), and in ecologically valid scenarios. These heterogeneous results could either indicate implicit, individual prioritization strategies or a limitation due to task difficulties. Thus, participants may either have not perceived a risk to their health out of the virtual reality which would limit the extent to what VR scenarios transmit a real life impression or might have been limited by ceiling effects within some tasks. Overall, it appears that realistic loading tasks can be motivating enough to override older persons' concerns about postural stability. However, it has to be mentioned that in our study, participants were allowed to keep one hand to the treadmill's handrail which might have influenced participant's perceived postural control. In this vein, Lövdén et al. (2005) revealed that older adults' navigation performance improves when holding on to a handrail. Thus, future studies should systematically investigate the influence of additionl support and might also assess general as well as test set up-related anxiety scores such as fear of falls.

Inconsistent with our third expectation, effects of multitasking were not consistently more pronounced in the visual compared to the auditory modality (cf. **Tables 3**, **4**). More pronounced multitasking effects in the visual than auditory condition are in accordance with an earlier virtual-driving study where visual and auditory loading tasks were presented blockwise (Chaparro et al., 2005). In our study, however, stronger effects of the visual modality were observed for only a part of the age × parameter combinations. This was most striking for *Stay Time*, for which the visual task modality (in YA as well as in OA) caused the highest overall MTE of all parameters, implicating that within this phase of the crossing process, vision might play an indispensable role. However, for other combinations, both modalities yielded similar effects or the auditory modality even yielded stronger effects e.g., for *Back Alley Speed* which was surprisingly more effected by the auditory task modality. We therefore found no unequivocal support for the multiple resource model in our ecologically valid scenario. Possibly, our multitasking scenario was complex enough to give participants a choice exactly what resources they allocated to the task at hand. As a consequence, participants' strategic choices could have upset any strict relationship between task modality and multitasking effects.

The lack of a consistent relationship between task modality and multitasking performance is particularly striking for our loading task: multitasking effects on *Typing Reaction Time* were more pronounced in the visual modality, while those on *Typing Accuracy* were stronger in the auditory modality. We contribute this particular dissimilarity to the fact that in the German language, the ten's and one's of numbers are spoken in reversed order (e.g., "two hundred and five-and-forty" instead of "two hundred and forty-five"). If participants pressed the keys in the same order in which digits were spoken, this would have reduced.

In conclusion, our findings confirm that age-related deficits of multitasking exist even in ecologically valid scenarios, and

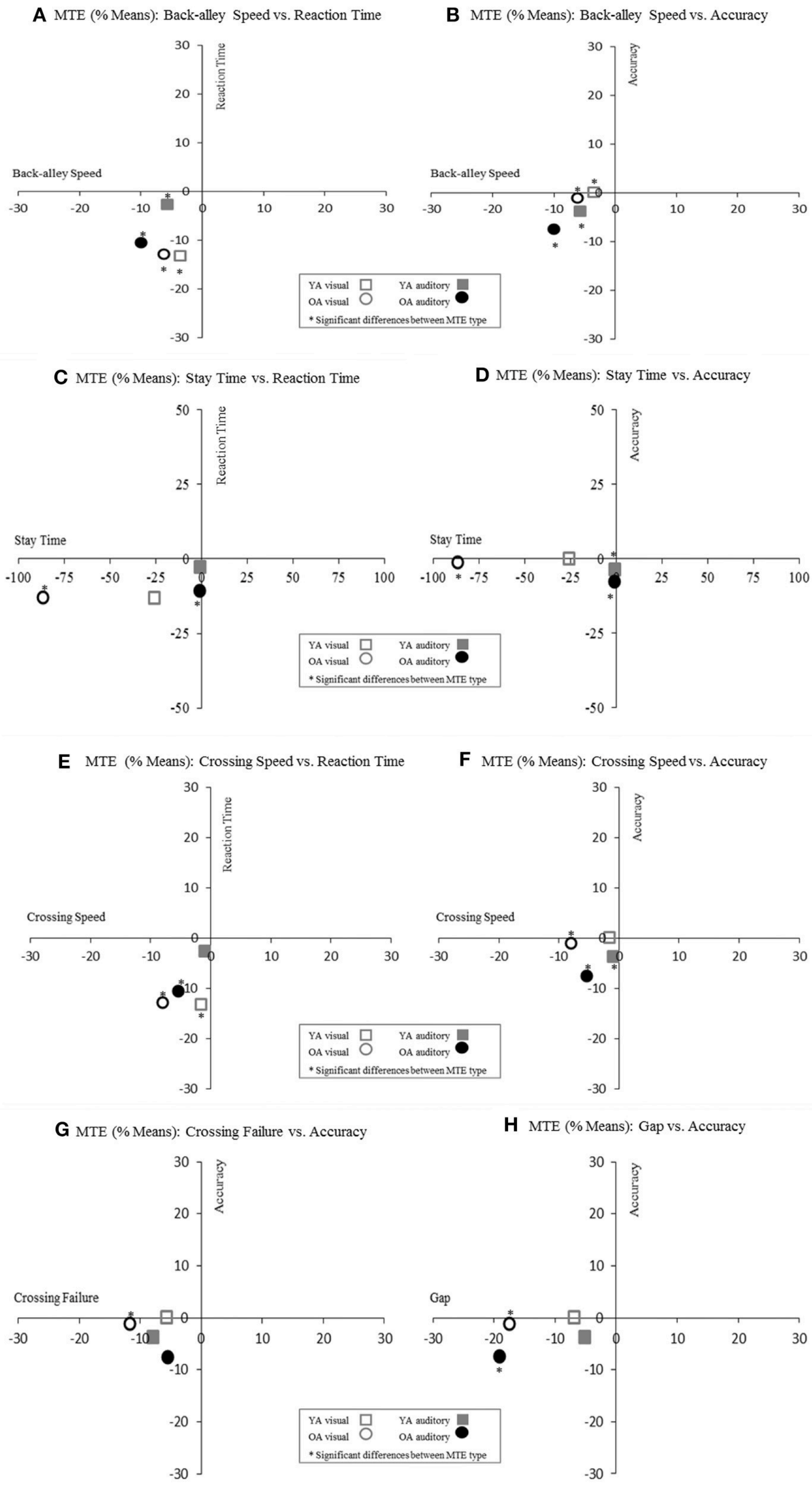

FIGURE 4 | Multitasking Effects (MTE) distribution (Means in %) grouped by age (YA vs. OA) and task type (street crossing related vs. typing related).

document that those deficits can emerge in both concurrent tasks. However, our findings provide no unequivocal support for the posture-first hypothesis and for the multiple-resource model. We attribute this lack of support to motivational and to strategic factors, which are controlled for in traditional laboratory paradigms but play a major role in realistic behavior.

AUTHOR CONTRIBUTIONS

CJ performed the acquisition of data and data analyses and wrote the drafts of the manuscript. CV-R as a senior author as well as OB contributed in terms of data selection, data analysis as well as in editing the manuscript and providing additional ideas at how to interpret our data. KW, UD and MH supported the data collection as well as the data analysis and proof read the manuscript.

ACKNOWLEDGMENTS

This research was supported by a grant within the Priority Program, SPP 1772 from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), grants BO 649/22-1 and VO 1432/19-1 and by a grant of the European Social Fund and the Free State of Saxony (CJ).

We wish to thank Wim Van Winsum and Thomas Kesnerus for the modification of the simulator software and constant support. We thank Rieke Schmale, Gisli Barthelmess, Sandra Goertz, Verena Herzoff, Clara Rentz, Damaris Wallmeroth, Jacqueline Kasemir, Lorenz Baumjohann, Martin Rebro. Karim Aly, Stella Henn, Vincent Drießen, Isarn Babel, Maria Andrea Neubert, Malte Liebl-Wachsmuth, and Karolina Boxberger for their assistance in data collection and data analyses.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 12 March 2018
doi: 10.3389/fpsyg.2018.00311

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Effects of Single Compared to Dual Task Practice on Learning a Dynamic Balance Task in Young Adults

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Background: In everyday life, people engage in situations involving the concurrent processing of motor (balance) and cognitive tasks (i.e., "dual task situations") that result in performance declines in at least one of the given tasks. The concurrent practice of both the motor and cognitive task may counteract these performance decrements. The purpose of this study was to examine the effects of single task (ST) compared to dual task (DT) practice on learning a dynamic balance task.

Methods: Forty-eight young adults were randomly assigned to either a ST (i.e., motor or cognitive task training only) or a DT (i.e., motor-cognitive training) practice condition. The motor task required participants to stand on a platform and keeping the platform as close to horizontal as possible. In the cognitive task, participants were asked to recite serial subtractions of three. For 2 days, participants of the ST groups practiced the motor or cognitive task only, while the participants of the DT group concurrently performed both. Root-mean-square error (RMSE) for the motor and total number of correct calculations for the cognitive task were computed.

Results: During practice, all groups improved their respective balance and/or cognitive task performance. With regard to the assessment of learning on day 3, we found significantly smaller RMSE values for the ST motor (d = 1.31) and the DT motor-cognitive (d = 0.76) practice group compared to the ST cognitive practice group but not between the ST motor and the DT motor-cognitive practice group under DT test condition. Further, we detected significantly larger total numbers of correct calculations under DT test condition for the ST cognitive (d = 2.19) and the DT motor-cognitive (d = 1.55) practice group compared to the ST motor practice group but not between the ST cognitive and the DT motor-cognitive practice group.

Conclusion: We conclude that ST practice resulted in an effective modulation of the trained domain (i.e., motor or cognitive) while only DT practice resulted in an effective modulation of both domains (i.e., motor and cognitive). Thus, particularly DT practice frees up central resources that were used for an effective modulation of motor and cognitive processing mechanisms.

Keywords: skill acquisition, stabilometer, postural control, cognitive interference task, human

OPEN ACCESS

Edited by:
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Reviewed by:
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Rahul Goel,
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *06 November 2017*
Accepted: *26 February 2018*
Published: *12 March 2018*

Citation:
Kiss R, Brueckner D and Muehlbauer T (2018) Effects of Single Compared to Dual Task Practice on Learning a Dynamic Balance Task in Young Adults. Front. Psychol. 9:311. doi: 10.3389/fpsyg.2018.00311

INTRODUCTION

In everyday life, situations involving the processing of motor (balance) and cognitive tasks simultaneously [i.e., dual task (DT) situations] represent the norm rather than an exception. For example, recalling schedules for an upcoming team meeting while walking toward the meeting room or talking to colleagues on the phone while crossing a busy street is common in our daily routines. Previous studies in healthy young adults investigating DT situations that involved a balance task (e.g., standing or walking) and a cognitive interference task (e.g., serial subtraction of numbers, memorizing words) primarily reported decrements in balance (i.e., increased postural sway, reduced gait speed) and/or in cognitive (i.e., reduced number of correct calculations, increased error rates) task performance. In fact, Chong et al. (2010) proved that the concurrent execution of a serial subtraction task while standing had a significant detrimental impact on balance (i.e., increase in body sway) and on computation (i.e., decrease in speed and accuracy) performance in healthy young adults (mean age: 25 years; *SD*: 3 years). In another study, Beauchet et al. (2005) showed significant performance decrements in DT compared to single task (ST) condition in young adults (mean age: 24 years; *SD*: 3 years), that is slower gait speed and a reduced number of enumerated figures.

Performance decrements during DT situations have previously been explained by limited cognitive capacities (i.e., "central overload") (Pashler, 1994) and/or cognitive interference when two tasks share the same processing resources (Wickens, 2008). Well-established theories that have widely been used to explain deficits in DT performance are the concepts of a central processing bottleneck ("single channel model") (Pashler, 1994; Pashler and Johnston, 1998) and the capacity sharing model (Tombu and Jolicoeur, 2003). The single channel model states that cognitive operations are carried out sequentially and a bottleneck arises whenever two tasks require a critical amount of cognitive processing capacity at the same time. On the other hand, the capacity sharing model argues that there is a pool of processing resources or networks that can be distributed between different tasks. Whenever more processing resources are devoted to one task, only limited processing capacity remains for the other networks and tasks and performance deficits in the given tasks arise.

To counteract these decrements in motor-cognitive performance and to improve cognitive as well as motor processing capacities in DT situations, the concurrent practice of both the motor (balance) and the cognitive task may represent a promising approach. Indeed, it has been shown that balance training induces a shift in activation from cortical to subcortical areas (Taube, 2012), indicating an effective modulation of central processing mechanisms (Taube et al., 2007, 2008). In old adults, it is well-documented that DT practice is suitable to improve balance and/or cognitive task performance under DT test conditions (Silsupadol et al., 2009a,b; Hiyamizu et al., 2012; Uemura et al., 2012). However, only a few studies are available in the literature that examined the effects of ST compared to DT practice on balance and cognitive task performance in healthy young adults. For example, Pellecchia (2005) examined the effect of ST versus DT training on balance and cognitive task performance in healthy adults aged 18–46 years. DT training included concurrent practice of the balance (i.e., quiet standing on a compliant surface) and cognitive (i.e., serial three subtractions) task while ST training consisted of practicing the balance and cognitive task separately. Results showed significantly less postural sway in the DT but not in the ST training group when concurrently performing both the balance and cognitive task; yet no significant group differences were detected for cognitive task performance under DT test condition. In another study, Worden and Vallis (2014), investigated the impact of ST compared to DT training on obstacle walking and auditory Stroop task performance in healthy young adults (mean age: 23 years; *SD*: 2 years). DT training included the practice of both tasks simultaneously and ST training consisted of practicing the cognitive task only. They found that only participants in the DT training group significantly improved their walking and Stroop task performance under DT test condition. In summary, studies on the effects of DT practice on balance and cognitive task performance under DT test condition in healthy young adults have shown conflicting evidence (i.e., improvements in both tasks versus improvements in the motor task only). Thus, further research is needed to clarify the impact of ST versus DT training on both balance and cognitive task performance in healthy young adults.

Therefore, the aim of this study was to examine the effects of ST practice (i.e., motor or cognitive task training only) compared to DT practice (i.e., concurrent motor and cognitive task training) on learning a dynamic balance task in healthy young adults. We expected that all three groups would significantly enhance their respective motor (balance) and/or cognitive task performance during 2 days of practice. With regard to the assessment of learning on day 3, we further hypothesized significant group differences during DT test condition in favor of the DT practice group for both motor and cognitive task performance.

MATERIALS AND METHODS

Participants

Forty-eight healthy college student volunteers were randomly assigned to either a ST motor practice group (n = 16; eight men, eight women; mean age: 25.0 years; *SD*: 3.1 years), a ST cognitive practice group (n = 16; eight men, eight women; mean age: 24.4 years; *SD*: 1.9 years), or a DT motor-cognitive practice group (n = 16; eight men, eight women; mean age: 26.1 years; *SD*: 3.4 years). The participants had no prior experience with the experimental tasks and were not aware of the specific purpose of this study. All subjects signed informed consent forms prior to the experiment. The Human Ethics Committee at the University of Duisburg-Essen, Faculty of Educational Sciences approved the study protocol.

Apparatus and Tasks

Dynamic Balance Task

The motor task required participants to balance on a stability platform (Lafayette Instrument, Model 16030, Lafayette, CO, United States). The stability platform consists of a 65 × 107-cm wooden platform, allowing a maximum deviation of 15° from the horizontal to either side of the platform (**Figure 1**). A safety rail mounted to the stability platform was used to prevent participants from falling if they lost their balance. Participants were instructed to remain in balance, i.e., to keep the stability platform in a horizontal position for as long as possible during each 90-s trial (**Figure 1A**). A millisecond timer measured time in balance at a sampling rate of 25 Hz. Time in balance was computed when the platform was within ±3° of horizontal position. Additionally, platform position data were exported from the analysis software PsymLab and used to calculate the root-mean-square error (RMSE) in degrees.

Serial Subtraction Task

The cognitive task was an arithmetic task, in which the participants loudly recited serial subtractions of three. The subtraction started from a randomly selected number between 300 and 900 that was given by the experimenter (Pellecchia, 2005). If a subject miscalculated, the false calculation was noted. When correctly continuing the serial three subtractions, only one error was noted (i.e., no consequential errors were registered). The total number of subtractions minus the number of subtraction mistakes made during the task was used as outcome measure. Thus, the higher the total number of correct subtractions, the better the cognitive task performance.

Procedure

In the ST motor and the ST cognitive practice group, participants performed the dynamic balance or cognitive task only, while in the DT motor-cognitive practice group they practiced the dynamic balance task and concurrently performed the cognitive task (i.e., serial three subtractions). All participants were informed that the motor task was to keep the stability platform in the horizontal position for as long as possible during each 90-s trial. Each trial started with the platform in horizontal position and arms grasping the safety rail (**Figure 1B**). Approximately 15 s before the start of a trial, the experimenter asked the participant to step on the platform without shoes. About 3 s before the start of a trial, the experimenter provided the starting number for the serial subtraction task to the participants of the DT motor-cognitive practice group. At the start signal, the participant attempted to move the platform, and data collection began. The arithmetic interference task was chosen because it has previously been shown to mitigate balance performance in healthy young adults (Pellecchia, 2003, 2005; Granacher et al., 2011). All participants performed seven 90-s practice trials on each of two consecutive days of practice under their respective treatment conditions. A 90-s rest interval was given between trials. Knowledge of results (i.e., time in balance and/or total number of correct calculations) was provided after each trial. To assess the learning effects of the different practice conditions, the participants were tested under DT test condition 24 h later (on day 3) without providing knowledge of results.

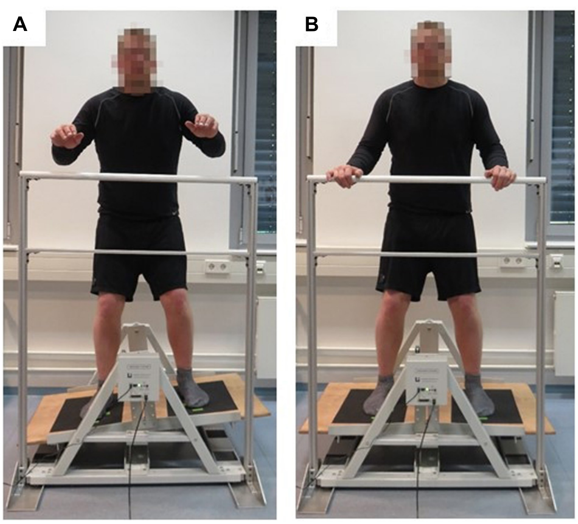

FIGURE 1 | Illustration of a participant balancing **(A)** and standing **(B)** on the stability platform (stabilometer).

Statistical Analyses

During acquisition on day 1 and day 2, the RMSE was analyzed in a 2 (group: ST motor practice, DT motor-cognitive practice) × 2 (day: day 1 to 2) × 7 (trial: trial 1 to 7) analysis of variance (ANOVA) with repeated measures on days and trials. In addition, the total number of correct calculations during acquisition was analyzed in a 2 (group: ST cognitive practice, DT motor-cognitive practice) × 2 (day: day 1 to 2) × 7 (trial: trial 1 to 7) ANOVA with repeated measures on days and trials. During testing on day 3, RMSE and total number of correct calculations while testing under DT condition were analyzed using a one-way ANOVA. Additionally, Cohen's d was calculated to determine whether a statistical difference was practically meaningful as small ($0 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$). All analyses were performed using the Statistical Package for Social Sciences (SPSS) version 24.0 and significance level was set at $p < 0.05$.

RESULTS

Days 1 and 2: Acquisition

Root-Mean-Square Error

For a participant from the DT motor-cognitive practice group, examples of platform position data from the first trial on day 1, from the first trial on day 2, and from the DT test condition on day 3 are provided in **Figures 2A–C**. As can be seen from **Figure 3**, both the ST motor and the DT motor-cognitive practice group decreased their RMSE across the 2 days of practice. The Group × Day × Trial ANOVA revealed statistically significant main effects of day, $F_{(1,30)} = 182.581$, $p < 0.001$, $d = 4.94$ and trial, $F_{(6,180)} = 112.333$, $p < 0.001$, $d = 3.87$ but not of group,

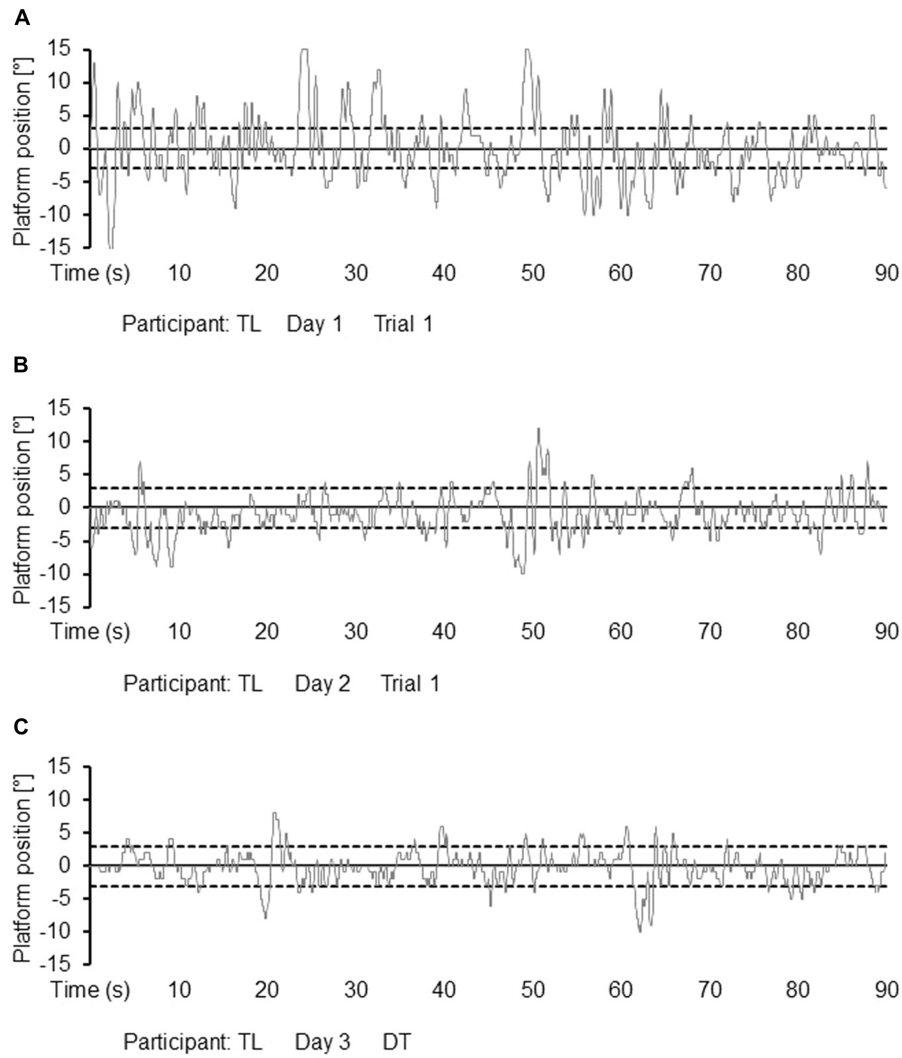

FIGURE 2 | Examples of platform position data profiles for participant TL from the DT motor-cognitive practice group for trial 1 during acquisition on day 1 **(A)**, for trial 1 during acquisition on day 2 **(B)**, and during dual task testing on day 3 **(C)**. DT, dual task.

$F_{(1,30)} = 1.108$, $p = 0.301$, $d = 0.39$. Additionally, we found a significant Group × Day × Trial interaction, $F_{(6,180)} = 3.713$, $p = 0.002$, $d = 0.70$ indicating relatively greater improvements on day 1 than on day 2 in favor of the ST motor practice group.

Total Number of Correct Calculations

Figure 4 displays that both the ST cognitive and the DT motor-cognitive practice group increased their total number of correct calculations over the two practice days. The Group × Day × Trial ANOVA revealed statistically significant main effects of day, $F_{(1,30)} = 201.406$, $p < 0.001$, $d = 5.17$, trial, $F_{(6,180)} = 50.395$, $p < 0.001$, $d = 2.59$, and group, $F_{(1,30)} = 6.402$, $p = 0.017$, $d = 0.92$. The main effect of group indicates a higher level for the total number of correct calculations for the ST cognitive compared to the DT motor-cognitive practice group. The Group × Day × Trial interaction, $F_{(6,180)} = 1.428$, $p = 0.206$, $d = 0.43$ did not reach the level of significance.

Day 3: Testing

Root-Mean-Square Error

The one-way ANOVA showed significant differences between the three groups, $F_{(2,45)} = 6.759$, $p = 0.003$, $d = 0.48$. *Post hoc* comparisons indicated significantly smaller RMSE values under the DT test condition for the ST motor ($p = 0.002$, $d = 1.31$) and the DT motor-cognitive ($p = 0.040$, $d = 0.76$) practice group compared to the ST cognitive practice group. No significant difference was found between the ST motor and the DT motor-cognitive practice group (**Figure 3**).

Total Number of Correct Calculations

The one-way ANOVA revealed significant differences between the three groups, $F_{(2,45)} = 18.730$, $p < 0.001$, $d = 0.61$. *Post hoc* comparisons indicated significantly larger total numbers of correct calculations under the DT test condition for the ST cognitive ($p < 0.001$, $d = 2.19$) and the DT motor-cognitive

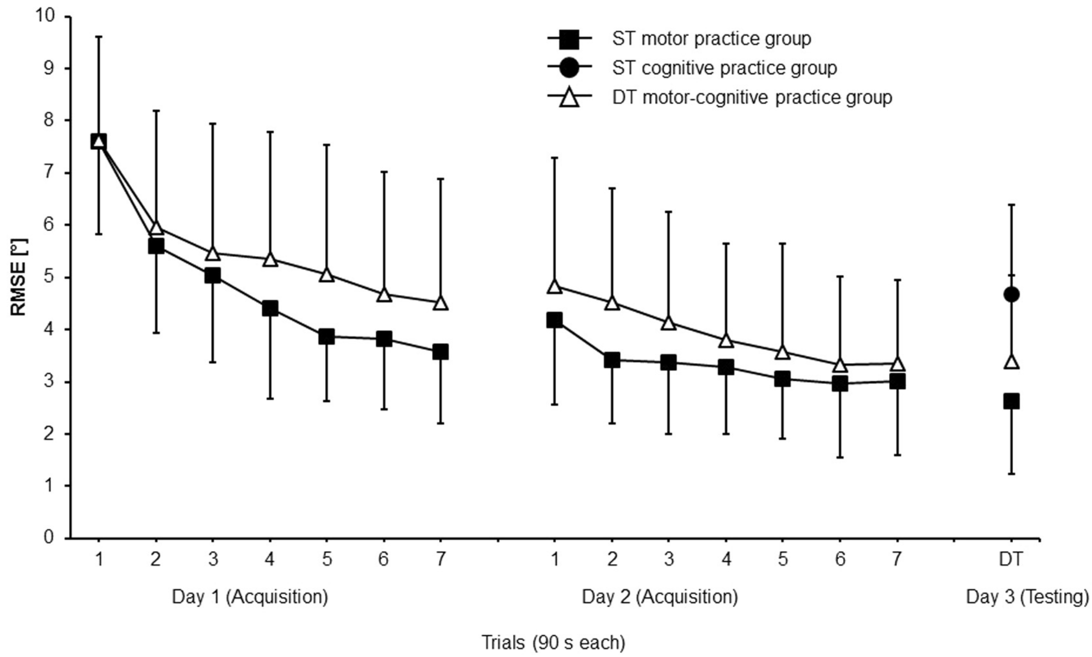

FIGURE 3 | Root-mean-square error (RMSE) of the ST motor and the DT motor-cognitive practice groups during acquisition (day 1 and day 2) and of the ST motor, the ST cognitive, and the DT motor-cognitive practice groups during testing (day 3). Values represent means and standard deviations. ST, single task; DT, dual task.

($p < 0.001$, $d = 1.55$) practice group compared to the ST motor practice group. No significant difference was detected between the ST cognitive and the DT motor-cognitive practice group (**Figure 4**).

DISCUSSION

In the present study, we compared the effects of DT practice (i.e., concurrent motor and cognitive task training) compared to ST practice (i.e., motor or cognitive task training only) on learning a dynamic balance task in healthy young adults. In accordance with our first hypothesis, we found that all groups significantly improved their respective motor (i.e., decreased RMSE) and/or cognitive (i.e., increased total number of correct calculations) task performance across the 2 days of practice. Contrary to our second hypothesis, we detected similar but not significantly better motor and cognitive task performance for the DT practice group compared to the ST practice groups under DT test condition. However, the ST practice groups improved their performance only in the trained domain. In other words, ST motor practice resulted in enhanced motor but not cognitive performance and the ST cognitive practice lead to better cognitive but not motor performance in DT condition. Only DT practice resulted in improvements in both domains (i.e., enhanced motor and cognitive performance in DT condition).

Motor (Balance) Task Performance

In contrast to previous research (Pellecchia, 2005; Worden and Vallis, 2014), we found similar but not significantly better balance performance under DT test condition for the DT motor-cognitive practice group compared to the ST motor practice only group. Methodological differences in terms of the used balance task during practice may account for the discrepancies in findings. In this regard, a static balance task (i.e., quiet standing) was used in the study of Pellecchia (2005) and a dynamic balance task (i.e., crossing obstacles while walking) was applied by Worden and Vallis (2014). We also used a dynamic balance task but in contrast to the demands of the walking task used by the latter authors (i.e., stabilizing the center of mass within the base of support during ambulation to adequately perform the task), our dynamic balance task required participants to keep their balance on an unstable but stationary platform and not during ambulation. There is evidence in young adults that static and dynamic components of balance are not related to each other (Muehlbauer et al., 2013). Thus, it can be speculated that different neuromuscular mechanisms are responsible for the regulation of standing (Pellecchia, 2003) and/or walking (Worden and Vallis, 2014) compared to balancing on a stability platform.

A possible 'ceiling effect' may additionally account for the non-significant differences between the motor and the motor-cognitive practice group in balance task performance under DT test condition. In other words, the applied training volume (i.e., number of practice trials multiplied by duration per trial) resulted in an overlearning effect (i.e., automatization of the balance task), thus increasing the individuals' capacity to perform the cognitive task during DT (i.e., mitigating cognitive task interferences). Yet, previous studies that also used the stabilometer device applied the same or a higher training volume to induce practice-related changes in balance performance (Wulf et al., 1998, 2003;

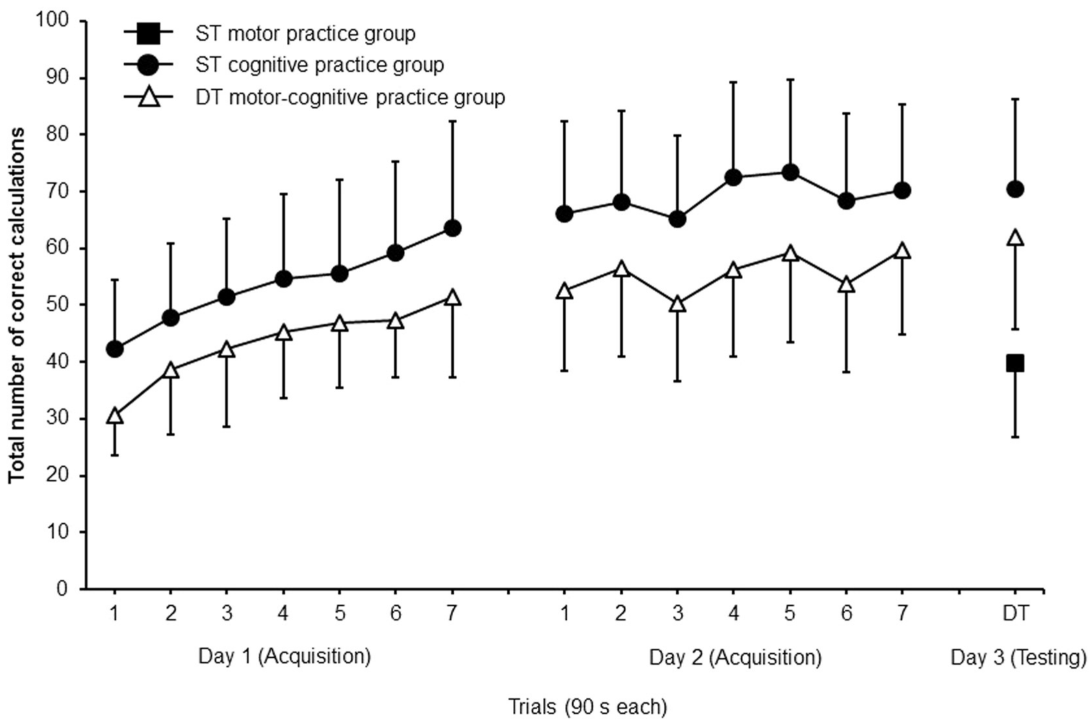

FIGURE 4 | Total number of correct calculations of the ST cognitive and the DT motor-cognitive practice groups during acquisition (day 1 and day 2) and of the ST motor, the ST cognitive, and the DT motor-cognitive practice groups during testing (day 3). Values represent means and standard deviations. ST, single task; DT, dual task.

Shea and Wulf, 1999; McNevin et al., 2003). Alternatively, the used cognitive interference task was not difficult enough to elicit decrements in balance task performance under DT test condition. However, serial three subtractions were used in former research and resulted in an effective manipulation of attentional demand in healthy young adults indicated by a deteriorated balance performance (Pellecchia, 2003; Granacher et al., 2011; Beurskens et al., 2016).

Cognitive Task Performance

Contrary to previous research (Worden and Vallis, 2014), we detected similar but not significantly better cognitive task performance for the DT motor-cognitive practice group compared to the ST cognitive practice group in DT test condition. However, only DT practice resulted in an effective modulation of both domains (i.e., motor and cognitive) while ST practice resulted in an effective modulation of the trained domain (i.e., motor or cognitive) only. Thus, our findings on motor and cognitive task performance under DT test condition suggest that particularly DT practice can result in an effective concurrent execution of a serial subtraction and a dynamic balance task. What are likely explanations for this observation? Particularly DT practice seems to be suitable to economize cognitive as well as motor processing capacities during DT situations that are then used to improve arithmetic computation and postural control. Previously, it has been shown that structural and functional changes in the human brain are likely to occur after relatively short periods of practice on the stability platform (i.e., after 2 of 6 practice sessions using 30-s trials) in healthy young adults (Taubert et al., 2010, 2011, 2016). That is, increased gray matter volume in frontal and parietal regions of the brain (Taubert et al., 2010) and increased functional fronto-parietal network connectivity (Taubert et al., 2011). These findings are indicative for an effective modulation of central processing mechanisms following practice of the stabilometer task. Also, the "challenge point framework," proposed by Guadagnoli and Lee (2004) might be suitable to explain our findings. The authors state that information about the task to be learned and its subjective difficulty is crucial for the learning process. The DT practice situation in our study might have provided the right amount of task difficulty and information to facilitate motor and cognitive learning processes.

Results of the present study revealed significantly improved motor (balance) and/or cognitive task performance across 2 days of acquisition. In addition, we found similar motor and cognitive task performance for the DT practice group compared to the ST practice groups under DT test condition. However, participants in the ST practice groups improved their trained performance only (i.e., motor or cognitive performance) while subjects in the DT motor-cognitive practice group improved both, their motor and their cognitive performance. Our findings are indicative of an effective modulation of the trained domain (i.e., motor or cognitive) only through ST practice but an effective modulation of both domains (i.e., motor and cognitive) through DT practice.

Thus, DT practice seems to be suitable to free up central resources that were then used for an effective modulation of motor (postural control) and cognitive (arithmetic computation) processing mechanisms.

Limitations

Our study includes two limitations that need to be addressed. First, on day 1 we did not assess the initial level of ST and DT performance to compare it with the respective performance on day 3. Consequently, we are not able to adjust our results to a potential difference in ST and DT performance between groups at baseline. Second, we investigated a cohort of healthy young adults whose motor and cognitive capacities are well-developed. Thus, this cohort might be less likely to be influenced by DT situations compared to more impaired cohorts, such as older adults or clinical cohorts. However, even young adults showed impaired motor and/or cognitive performance during DT situations in previous studies (Pellecchia, 2003, 2005; Granacher et al., 2011) and thus might benefit from specific DT practice protocols. Although, a generalization of our results to other (clinical) cohorts is not advisable.

AUTHOR CONTRIBUTIONS

RK developed the research design and was the primary author of the manuscript. DB collected the data and gave edits throughout the creation of the manuscript. TM helped to create the research design and provided content and edits to the manuscript.

ACKNOWLEDGMENTS

We acknowledge support by the Open Access Publication Fund of the University of Duisburg-Essen. Further, we wish to acknowledge the contributions to participant recruitment and data collection made by Laura Wich, Marius Simon, and Stephanie Kramer.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 22 December 2017
doi: 10.3389/fpsyg.2017.02241

Implicit and Explicit Knowledge Both Improve Dual Task Performance in a Continuous Pursuit Tracking Task

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The goal of this study was to investigate the effect of predictability on dual-task performance in a continuous tracking task. Participants practiced either informed (explicit group) or uninformed (implicit group) about a repeated segment in the curves they had to track. In Experiment 1 participants practices the tracking task only, dual-task performance was assessed after by combining the tracking task with an auditory reaction time task. Results showed both groups learned equally well and tracking performance on a predictable segment in the dual-task condition was better than on random segments. However, reaction times did not benefit from a predictable tracking segment. To investigate the effect of learning under dual-task situation participants in Experiment 2 practiced the tracking task while simultaneously performing the auditory reaction time task. No learning of the repeated segment could be demonstrated for either group during the training blocks, in contrast to the test-block and retention test, where participants performed better on the repeated segment in both dual-task and single-task conditions. Only the explicit group improved from test-block to retention test. As in Experiment 1, reaction times while tracking a predictable segment were no better than reaction times while tracking a random segment. We concluded that predictability has a positive effect only on the predictable task itself possibly because of a task-shielding mechanism. For dual-task training there seems to be an initial negative effect of explicit instructions, possibly because of fatigue, but the advantage of explicit instructions was demonstrated in a retention test. This might be due to the explicit memory system informing or aiding the implicit memory system.

Keywords: multitasking, implicit motor learning, continuous tracking task, predictability, sequence learning

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *04 September 2017*
Accepted: *11 December 2017*
Published: *22 December 2017*

Citation:
Ewolds HE, Bröker L, de Oliveira RF, Raab M and Künzell S (2017) Implicit and Explicit Knowledge Both Improve Dual Task Performance in a Continuous Pursuit Tracking Task. Front. Psychol. 8:2241. doi: 10.3389/fpsyg.2017.02241

INTRODUCTION

Dual-task studies reveal limitations in human behavior and are therefore an intriguing way to discover the functional properties of the cognitive and motor system. When two tasks are performed simultaneously a decrease in performance is usually observed. Several mechanisms have been proposed to explain this dual-task interference such as bottleneck theories (Welford, 1967; Pashler, 1994; Borst et al., 2010), capacity theories (Kahneman, 1973; Navon and Gopher, 1979; Wickens, 2008), and cross-talk models (Kinsbourne, 1981; Swinnen and Wenderoth, 2004). Bottleneck theories explain dual-task costs by proposing that certain processing stages (response selection and/or response execution) cannot be performed simultaneously. A bottleneck exists so that one task has to finish processing before the other may start, which causes a delay for the second task. Resource theories accept simultaneous processing but state that there is a finite resource (or resources) that put a limit on dual-task performance. Cross talk theories propose that dual-task costs mainly arise when the outcome of one task intervenes with the processing of another (Navon and Miller, 1987). So far these theories have not yielded practical solutions on how to improve dual-task performance (for an overview see Pashler, 1994). When casually observing motor behavior of humans in everyday situations however, it becomes apparent that seemingly successful dual-tasking is a common occurrence: walking down a busy street while talking, or driving a car while listening to the radio for instance. We argue that a key feature of such successful multi-tasking is the predictable nature of at least one of the tasks.

Another feature that theoretically reduces dual-task costs is automatic processing, since it leaves the bottleneck open (Ruthruff et al., 2006b) or frees up limited resources, in order to be able to perform a different task. Neumann (1984) stated that automatic task processing depends on the fulfillment of two demands. According to Neumann there are three sources that specify the parameters that are sufficient to carry out an action: first, procedures stored in long term memory (skills), second, input information from the environment and third attentional mechanisms. As long as skills in conjunction with input information directly specify the parameters of the movement it can be completed without using attentional mechanisms and attentional capacity, and without leading to conscious awareness. Frith and Wolpert (2000) argue that this is exactly how the motor system, equipped with forward models, seems to function. That is, as long as a situation is predictable, for instance going down a familiar set of stairs, and there is no mismatch between expected consequences and results, movements are largely automatic (they occur without awareness or attentional control). Indeed, it would be highly disadvantageous if we were aware of every eye movement or postural adjustment. Therefore, we hypothesize that automaticity and by extension dual-task performance is dependent on the predictability of a task.

One way to make a task predictable is through knowledge, either explicit or implicit. In the current paper implicit knowledge is defined as knowledge shown by performance in the absence of verbalizeable knowledge (Nissen and Bullemer, 1987; Heuer and Schmidtke, 1996). The role of implicit versus explicit knowledge in dual-task situations is controversial. In a review of serial reaction time (SRT) tasks and visuomotor adaptation tasks, Taylor and Ivry (2013) noted that explicit knowledge is mainly used in the planning of action goals while implicit processes are dominant in learning the parameters of movement execution. Although the implicit and explicit knowledge systems can operate in parallel there is evidence that in dual-task conditions only implicit knowledge aids multitask performance (Curran and Keele, 1993). When participants in Curran and Keele's study were explicitly informed about the sequence in an SRT task, they were much faster compared to non-informed participants, however, when a secondary task was introduced they performed equally to a group that learned the sequence implicitly. Curran and Keele argued that this possibly meant that only the implicit component of knowledge obtained by the informed group was of use in the dual-task situation. The advantage of implicit knowledge has also been demonstrated in sports and motor-related contexts. For instance, novices who learnt a tennis forehand implicitly showed better performance while making complex decisions compared to novices who learnt the forehand explicitly (Masters et al., 2008). In contrast, Blischke et al. (2010) showed that no dual-task costs remained when a key sequence task was learned explicitly and under dual-task conditions. The role of implicit and explicit knowledge in dual-task performance therefore remains unclear. As outlined earlier, we would argue that predictability could be a crucial factor in facilitating optimal dual-task performance, and accepting that implicit and explicit knowledge constitute predictability, both should improve dual-task performance.

Predictability is well-studied in SRT studies which entail simple discrete movements (e.g., Nissen and Bullemer, 1987; Curran and Keele, 1993). Implicit sequence learning is a robust effect found when participants are allowed to practice on this task but equally, performance on the task is easily improved by explicitly pointing out the sequence. In the current study we use a pursuit tracking task that requires continuous movements to track curves which has a less prominent explicit component than the SRT task. The continuous nature of the pursuit tracking task makes it an interesting alternative to the more often used short discrete tasks. It captures performance of real-world tasks such as driving which could be modeled as continuous tracking itself (Raab et al., 2013). The pursuit tracking task requires participants to track a target moving on a screen. The target follows an invisible sinusoidal curve on the screen which consists of three segments (Pew's paradigm, 1974). To investigate implicit learning, the middle segment remains constant throughout the trials, while the two outer segments vary. It has been demonstrated that this is a reliable manipulation to test for implicit learning, because participant's performance on the repeating segment is better than on random segments after several practice blocks, even though participants appear not to be aware of the repeating part (Pew, 1974; Wulf and Schmidt, 1997; Zhu et al., 2014; Künzell et al., 2016; de Oliveira et al., 2017).

In Experiment 1 we determined whether a repeated segment within the pursuit tracking task is learned under single task conditions, and if that results in better performance compared to random segments when a second task is introduced (an auditory go/no-go task). We expected better performance and even disappearance of dual-task costs for the repeated segment, which would confirm the hypothesis that tracking of the repeated segment is automatized. Whereas most studies investigating implicit learning in tracking have not tested the effect of explicit knowledge we added this condition to our experiment. Firstly this enables us to investigate the effect of explicit knowledge on a largely motoric task, secondly we are able to test the hypothesis that both types of knowledge would aid dual-task performance since both provide predictability. Experiment 2 was mostly identical to Experiment 1 with the key difference that learning took place under dual-task conditions. This has a practical reason since it can be argued that learning, especially in sports, rarely takes place in single-task conditions. In SRT tasks learning under dual-task conditions is often reduced but not abolished (Frensch et al., 1998). However, there might be a positive effect of a secondary task at later stages in the learning process because attending to well-learned motor skills seems to have a negative effect and this would be diminished in dual-tasking (Beilock et al., 2002). Therefore we may find reduced learning in Experiment 2 but possibly better performance in dual-task conditions compared to single-task conditions after learning.

EXPERIMENT 1

Materials and Methods

Participants

Participants were 37 university students that were divided into two groups: the *implicit group* had 20 participants ($M = 25.0$ years old, $SD = 2.2$) and the *explicit group* had 17 participants ($M = 25.1$ years old, $SD = 2.8$). All participants reported normal or corrected-to-normal vision and no reported neurological disorders. All participants gave informed consent prior to the start of the experiment and received remuneration of 20€ after completing the experiment. The research was approved by the local ethics committee of the University of Augsburg.

Experimental Setup

We asked participants to sit at a table in front of a joystick (Speedlink Dark Tornado) and a 24″ computer screen (144 Hz, 1920 × 1080 pixel resolution) which were 40 cm apart. The tracking program ran on a Windows 7 computer and data was recorded at 120 Hz. The stimuli of the auditory go/no-go task were delivered via Sennheiser stereo headphones and we recorded responses with a foot pedal (f-pro USB-foot switch, 9 cm × 5 cm). To ensure that tracking performance was not influenced by moving the joystick through the resting zone, which causes an irregularity in resistance, we made sure that the motion required to position the cursor from the upper to the lower edge of the screen fell within the upper half of the range of motion of the joystick on the y-axis.

Tasks and Display

The pursuit tracking task was replicated from Künzell et al. (2016). Random tracking segments were created from three segments j (left segment), k (middle segment) and l (right segment), with $j \neq k$, $k \neq l$, and $j \neq l$. The formula used to create the segments was taken from Wulf and Schmidt (1997):

$$f(x) = b_0 + \sum_{i=1}^{6} a_i \sin(i \cdot x) + b_i \cos(i \cdot x)$$

with a_i *and* b_i being a randomly generated number ranging from −4 to 4 and x in the range [0, 2π]. For this experiment 41 segments of similar length and number of extrema were selected. This is important to guarantee that learning is not attributed to difficulty of the segments (Chambaron et al., 2006). From the 41 segments available, the segment for each participant consisted of a (unique) middle repeated segment and two outer segments selected from the remaining 40, see **Figure 1** for an example. We chose the outer segments in such a way that each segment occurred an equal amount of time across and within participants. This meant that each participant would learn a different middle segment while the overall difficulty level was kept similar. For the tracking task, participants tracked a red target square along the invisible segment by controlling a cursor displayed as a white cross (both target and cursor fit in 19 × 22 pixels). Velocity of the target was constant along the curves, ensuring a uniform difficulty level across the trial. The velocity was the same as in Künzell et al. (2016) because they showed the most effective implicit learning at trial durations between 40 and 44 s.

The secondary task was an auditory go/no-go reaction time task, similar to studies investigating implicit sequence learning in SRT tasks (e.g., Heuer and Schmidtke, 1996). Participants pressed a pedal for high-pitched tones and ignored low-pitched tones (1086 and 217 Hz, 75 ms). On each trial the number of target sounds was 19 or 20 and the number of distractor sounds varied between 13 and 20. The minimum duration between sounds was 1001 ms and no sounds were placed earlier than 500 ms after the start of the trial or 500 ms before the end of the trial.

Procedure

After signing the informed consent, participants sat at the table and adjusted their seat and pedal. We tested participants individually. We explained that the cursor and the target moved automatically from left to right along a sinusoidal curve, and the goal was to keep the cursor as accurately as possible on the target by moving the joystick forward and backward (along the x-axis cursor movement was coupled to the target). Every five trials feedback reflecting average performance of the last five trials appeared on the screen.

On the first day participants completed 10 familiarization trials followed by 10 pre-test trials which were single-task tracking of a random segment. They then completed two training blocks with a repeated middle segment consisting of 40 trials each. Just before the training blocks, participants in the *explicit group* received information that there would be a repeating middle segment in the training blocks (no such instruction was given to the *implicit group*). On the second test day, a week later, participants were prepared for the go/no-go reaction time task by completing five familiarization trials followed by five pre-test trials. They then completed two training blocks as on day 1. At the end of the second test day, participants completed a test-block of 30 trials in different conditions in the following order: five trials as in the training block; five trials with a random middle segment; five trials as in the training block; 10 dual-task trials with the auditory task (participants were asked to pay equal attention to both tasks); five trials as in the training block (see **Figure 2**). After all blocks were completed, the *implicit group* answered a questionnaire to determine how aware they were of the repeated middle segment. The questionnaire contained seven questions designed to gradually probe participants about their knowledge of the repeated middle segment. The questions were: (1) Did you notice anything special during the experiment? (2) Was there something that helped or hindered you while performing

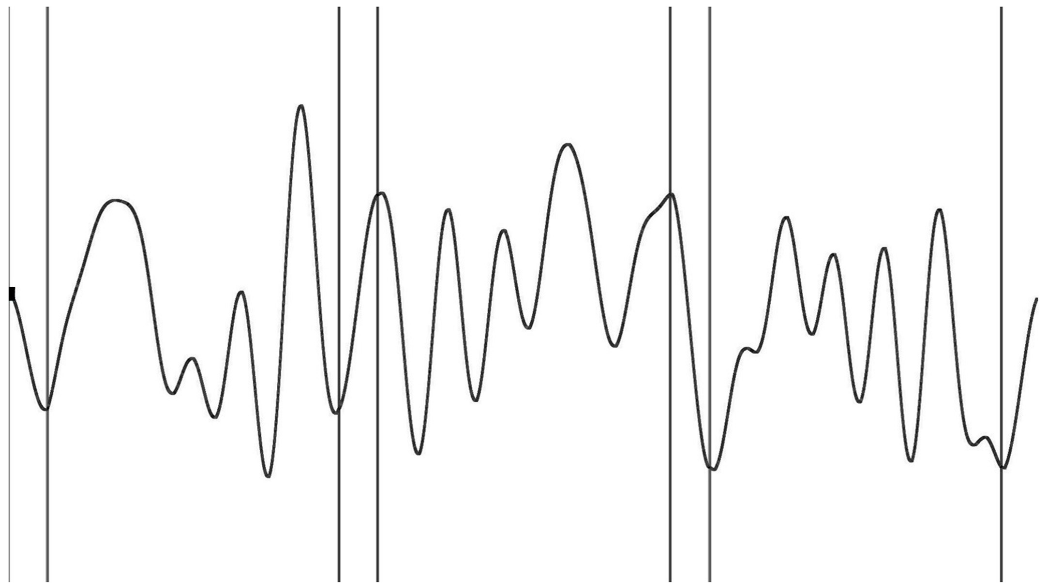

FIGURE 1 | Example of a trial in the tracking task. A trial consists of two random outer segments and a repeating middle segment connected by interpolated segments. Participants tracked a target that moved along the curves, the curves themselves were not visible during the experiment.

the tracking? (3) Did you apply any rules? (4) Did you notice anything special concerning the path of the target? (5) The target followed a certain path. Did you notice any segments in this path? (6) There were three segments in the path, the first, the middle and at the last segment. One of these segments was always repeated? Did you notice? (7) Which segment was the repeated segment, the first, the middle, or the last segment?

Data Analyses

The main dependent variable in the tracking task was the root mean square error (RMSE; Wulf and Schmidt, 1997) calculated from the difference between the target curve and the curve made by the user-controlled cursor. We followed the recommendations by Zhu et al. (2014) to take the average performance of the outer segments to compare with the repeated middle segment as they showed that performance deteriorates over time within a trial. For the auditory go/no-go task we recorded reaction times and errors. To test learning effects we submitted average RMSEs to a 4 × 2 × 2 mixed analysis of variance (ANOVA) with within subjects factors Training Block (four training blocks), Segment (middle segment vs. outer segments), and between subjects factors Group (implicit vs. explicit), with a significant Block × Segment interaction indicating learning of the repeating segment. Using the RMSEs from the test-block we checked learning by comparing performance on catch trials (random middle segment) compared to trials with a repeating middle segment. We performed two 2 × 2 × 2 mixed analyses of variance (ANOVA), with within-subjects factors Condition (single-task with repeating segment vs. single-task with random segment in the middle), and Segment (repeated middle segment vs. outer segments), and between-subjects factor Group (implicit vs. explicit). The single-task with repeating segment in the middle condition was the average of the three times we tested this condition, see **Figure 2**. The other 2 × 2 × 2 ANOVA included Condition (single-task vs. dual-task performance, both with a repeating middle segment), Segment and Group. The differences in performance between the repeated segment and the outer segments within the dual-task condition were tested using a paired-samples *t*-test. Finally, to test the effect of the tracking on reaction times (RTs) we performed a 2 × 2 analysis of variance (ANOVA) on reaction times, with factors Task (single or dual) and Group (implicit vs. explicit). A Greenhouse–Geisser correction was used when the assumption of sphericity was violated.

Results

First we checked whether the repeated segment was learned at all by analyzing tracking performance during the training sessions. There were overall improvements in tracking indicated by a main effect of Block, $F(2.22,77.72) = 21.52$, $p < 0.001$, $\eta_p^2 = 0.381$ (see **Figure 3**). Performance was better on the middle segment than on the outer segments as shown by the significant effect of Segment, $F(1,35) = 45.14$, $p < 0.001$, $\eta_p^2 = 0.563$ (middle $M = 1.42$, $SD = 0.24$; outer $M = 1.55$, $SD = 0.22$). Importantly, a Block × Segment interaction showed that, over the blocks, participants improved more on the repeating middle segment than on the random outer segments, $F(2.11,73.8) = 7.42$, $p < 0.001$, $\eta_p^2 = 0.175$ (see **Figure 3**). No effect of group was found, $F(1,35) = 1.99$, $p = 0.168$.

In order to prove that the repeating middle segment was learned we swapped it for a random middle segment during the test-block. Results revealed that performance for the condition with a repeating middle segment was better than with a random middle segment, $F(1,35) = 20.13$, $p < 0.001$, $\eta_p^2 = 0.365$, with a Condition (repeating middle segment vs. random middle

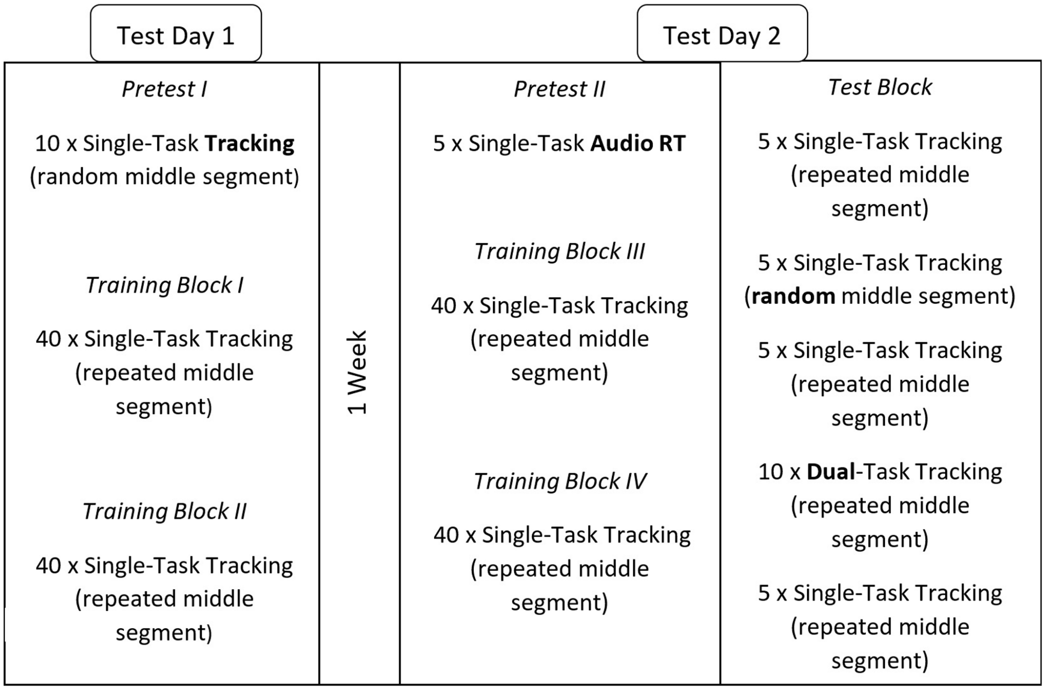

FIGURE 2 | Experimental design for Experiment 1. Both pretests were done for familiarization and stimuli were randomized to prevent learning. The break between training blocks was about a minute. In the test-block, the single-task trials with a random middle segment and the dual-task trials were nested within blocks with trials identical to those of the training blocks to minimize fatigue effects.

segment) × Segment (middle vs. outer segments) interaction proving that the difference is due to changes in the middle segment since difference in performance on the outer segments was 0.03 and 0.13 for the middle segment, $F(1,35) = 20.08$, $p < 0.001$, $\eta_p^2 = 0.376$, see **Figure 4**. An interaction between Condition and Group (implicit vs. explicit) indicated that the difference in performance with a repeating segment in the middle compared to a random segment in the middle was greater for the explicit group than for the implicit group ($M = 0.18$ cm, $SD = 0.04$ for the explicit group, $M = 0.09$ cm, $SD = 0.03$ for the implicit group), $F(1,35) = 4.17$, $p = 0.049$, $\eta_p^2 = 0.106$.

To test the effect of dual-tasking we compared the single task Condition with a repeated segment in the middle with the dual-tasking, see **Figure 4**. A main effect of Condition (Single-task vs. Dual-task) showed that performance in the dual-task condition deteriorated, $F(1,35) = 14.13$, $p = 0.001$, $\eta_p^2 = 0.228$. A main effect of Segment indicated better performance on the middle segment, $F(1,35) = 71.919$, $p < 0.001$, $\eta_p^2 = 0.673$, and a paired samples t-test revealed that during dual tasking, performance on the repeated segment ($M = 1.47$, $SD = 0.23$) was better than on the outer segments [$M = 1.59$, $SD = 0.21$; $t(36) = 6.64$, $p < 0.001$]. No main effect of Group could be found, $F(1,35) < 1$, $p = 0.637$, $\eta_p^2 = 0.006$.

For the second task, the auditory reaction time task, RTs lower than 200 ms and higher than 1000 ms were discarded, resulting in five discarded trials. We found a significant main effect of Condition, $F(1,33) = 26.78$, $p < 0.001$, $\eta_p^2 = 0.448$, because RTs were significantly slower in the dual-task condition ($M = 558$ ms, $SD = 58$) than in the audio-only pre-test ($M = 510$ ms, $SD = 57$). No effect of Group, $F(1,33) < 1$, $p = 0.681$, and no Condition × Group interaction was found, $F(1,33) < 1$, $p = 0.551$. In another ANOVA no significant effect of Segment, $F(1,35) = 1.681$, $p = 0.203$ could be found, indicating a repeating tracking segment did not lead to better performance on the reaction time task. We did not find a significant Group × Segment effect, $F(1,35) = 3.636$, $p = 0.065$.

Participants of the implicit group could not verbalize explicit knowledge about the repeated middle segment during the first five probing questions. For question 6 two participants said they noticed a repeating segment but for question 7 only one of them correctly identified the middle one as repeating. Answers to question 7, where participants were asked to say which segment was repeating even if they did not notice a repeating segment in question 6, were as follows: 4 said the first segment, 12 said the middle segment, 4 said the last segment.

Discussion

The purpose of this experiment was to investigate whether predictability helps dual-task performance. Predictability was gained by either implicit or explicit knowledge of the tracking task. Better performance for both groups on the predictable segment during dual-tasking shows that predictability indeed had a beneficial effect on dual-task performance. To the knowledge of the authors this study is the first to use a continuous tracking task to assess the benefit of knowledge gained in single task conditions to performance under dual task conditions. The fact

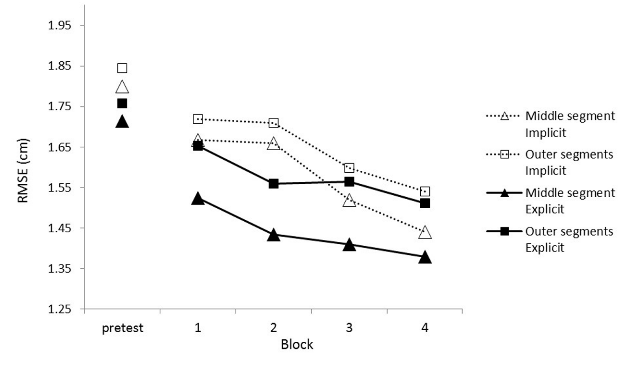

FIGURE 3 | Mean root mean square error (RMSE) scores throughout the training blocks. Training blocks 1–4 had repeating middle segments while the pre-test had random segments in the middle.

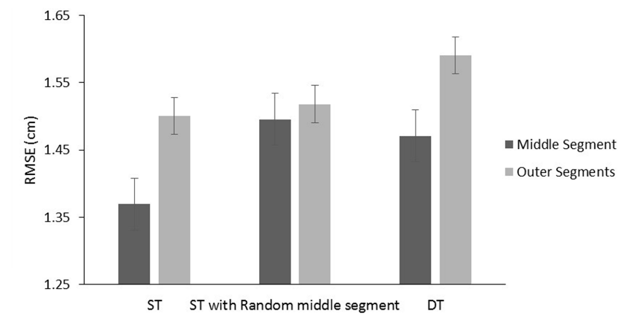

FIGURE 4 | Results of the test-block for the implicit and explicit group together, comparing the effect of putting a random segment in the middle and of dual-tasking with a repeating middle segment. ST, single-task; DT, dual-task.

that we found no difference between the explicit and implicit group is in line with SRT task performance under dual-task conditions (Curran and Keele, 1993), which is important because it shows that the implicit and explicit memory system might function similarly for discrete and more continuous tasks. It is often argued that the secondary task prevents the expression of explicit knowledge by using up all attentional resources, meaning the better dual task performance on the repeating segment is due to implicit knowledge only (Nissen and Bullemer, 1987; Curran and Keele, 1993; Heuer and Schmidtke, 1996). The design of the current study does not allow us to determine the contribution of implicit knowledge for the explicit group however.

The implicit group exhibited significantly larger improvements on the repeating middle segment than on the random outer segments and decreases in performance when the repeated segment was exchanged by a random segment, which we take as evidence for implicit learning. Furthermore, only one of the participants revealed explicit knowledge of the repeating segment in the questionnaire, noticing a repeating middle segment and subsequently correctly identifying the middle one. When forced to choose between the three segments, 12 of the 20 participants chose the middle segment. These results are unlike the awareness reported in previous studies (e.g., de Oliveira et al., 2017) and may suggest that participants gained more access to explicit knowledge about the repeating middle segment during the interview than they were aware of during the experiment itself. Another explanation comes from an informal interview after the current study which revealed that participants excluded the first and the last segment being repeated because they remembered that the first segment always started in the middle of the left side of the monitor and then sometimes went up or down. Similarly, the last segment ended by either coming from the top or bottom before ending in the middle at the right side of the monitor. From this they inferred that the middle segment must have been constant. Other authors have suggested that verbal reports might not be the ideal way to assess explicit knowledge in the tracking paradigm since the knowledge is not easily verbalized by its very nature, instead recognition or production of the tracking curve could be a more compatible way of measuring awareness of the repeating middle segment (Chambaron et al., 2006). In any case, the results of the questionnaire do indicate that during the training and test-block participants were unaware of the repeating middle segment.

The explicit group learned the repeating middle segment equally well as the implicit group. This is in contrast with SRT studies which show that knowing the sequence beforehand leads to very fast initial performance (lower RTs) compared to an implicit learning condition (Curran and Keele, 1993). It should be noted that in our study explicit knowledge was gained by instructing participants that the middle segment was always the same, rather than offering knowledge of what the repeating segment looked like beforehand. As such our methods are more in line with Caljouw et al. (2016) who instructed participants to look for the sequence in an SRT task in the explicit condition and found that the younger group, similar in age as the participants in our study, performed comparable to the implicit condition while the older group was worse compared to the implicit condition. The finding that explicit instructions do not benefit motor learning when compared with implicit instructions concurs with findings in whole body movement tracking tasks (Shea et al., 2001) and a catching task on the computer (Green and Flowers, 1991). The design of the current study does not allow for a complete dissociation of implicit and explicit knowledge, therefore it cannot be determined if the positive effect found in the explicit condition in dual-tasking is due to explicit knowledge itself or caused by the implicit learning system being unimpeded by the explicit instructions.

Dual-task costs in the reaction time task were not reduced by predictability of the tracking task. When the tracking task becomes more automatic or less taxing, bottleneck theories predict that processing should become more available for the RT task, either by bypassing the bottleneck (task automatization) or stage-shortening. Resource theories would predict freeing up of resources. Since dual-task costs did not disappear our findings are more in line with the idea of stage-shortening, where the processing stages in the bottleneck model are shortened, rather than automatization (Ruthruff et al., 2006a). However, it is problematic to identify a separate perception, response selection and execution phase in a continuous tracking task, although

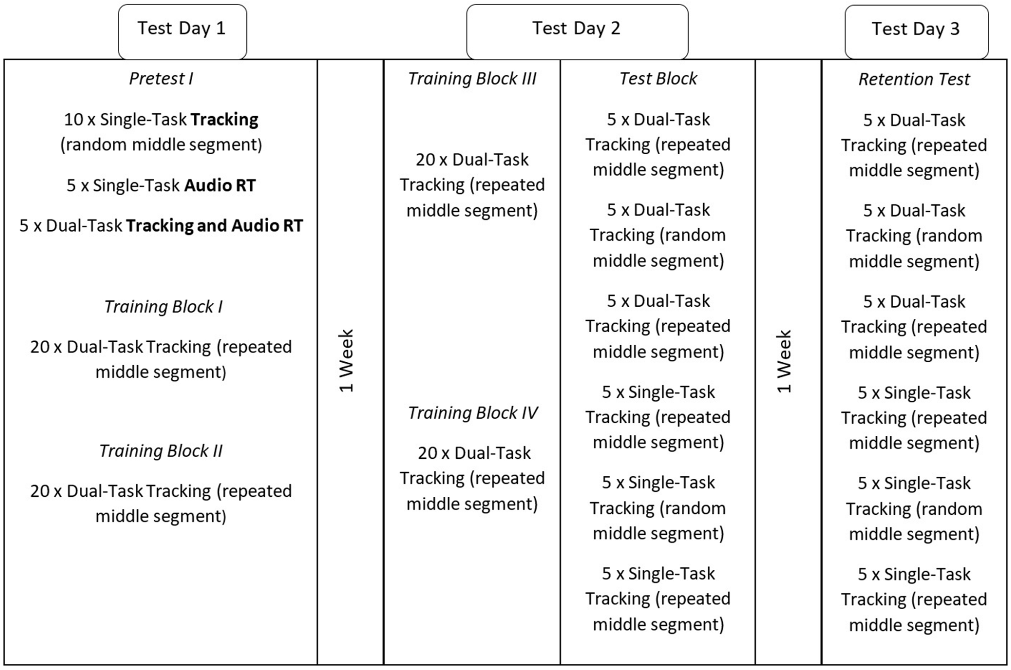

FIGURE 5 | The experimental design of Experiment 2. Note that tracking curves in the pre-test did not contain a repeating segment. The break between training blocks was about a minute. In the test-block and Retention Test, the single-task and dual-task trials with a random middle segment were nested within blocks with trials with a repeating segment to minimize fatigue effects.

some authors have tried to do so (Netick and Klapp, 1994). Our findings concur with the results of Heuer and Schmidtke (1996), who did not find an advantage of a learned repeating sequence in an SRT task on the reaction times of a simultaneous go/no-go auditory task with random tones. Further study is needed but it could be that predictability does not influence the mechanisms that produce dual-task interference, rather it improves dual-task performance by facilitating the predictable task only. Since, it could be argued that motor learning rarely takes place in single-task conditions; there usually are distractions or multiple tasks to be performed in many sports for instance, we now turn to the question what happens with implicit and explicit learning under dual-task conditions. Furthermore, since we didn't find an effect of informing participants about the repeating middle segment for single-task training we need to assess whether this information is beneficial or detrimental in a more demanding learning environment, further clarifying the role of implicit and explicit knowledge.

EXPERIMENT 2

In the second experiment we investigated whether a repeated tracking segment could still be learned under dual-task conditions, depending on whether instructions about the repeating middle segment were given or not. For comparable results we kept the setup and experimental procedure of Experiment 1 but asked participants to perform the training blocks under dual-task condition.

Conflicting results have been found in SRT studies regarding the question of whether implicit learning is still possible in dual-task conditions. Some studies have found acquisition of knowledge is eliminated or severely hampered with a secondary task (Nissen and Bullemer, 1987; Schmidtke and Heuer, 1997). However, Frensch et al. (1998) found that mainly the expression of knowledge is prevented but that implicit learning can still be demonstrated under single-task conditions although, with the same amount of training, the effect was weaker. Blischke et al. (2010) also investigated learning of the SRT with a secondary task. In the training phase this task was combined with a cognitively demanding secondary task and they found dual-task costs completely disappeared. However, since dual task costs appeared again when a different secondary task was used it seems unlikely that the SRT task had been automatized. This was in contrast to a previous study by Blischke (2001), where they found that a ballistic jumping task was completely automatized after dual-task practice. The authors suggested this finding might have been due to the explicit sequential component of both tasks in the SRT study favoring more cognitive control mechanisms (see also Saling and Phillips, 2007). Since the current study uses a task with a stronger motor component rather than an easy to verbalize explicit sequence we expect automatization, shown as an absence of dual-task costs, to be more likely. Furthermore, as learning under dual-task conditions is more resource demanding than single-task training we expect that explicitly informing the participants of the repeating segment might hamper performance, although some authors have suggested that activation of the explicit memory

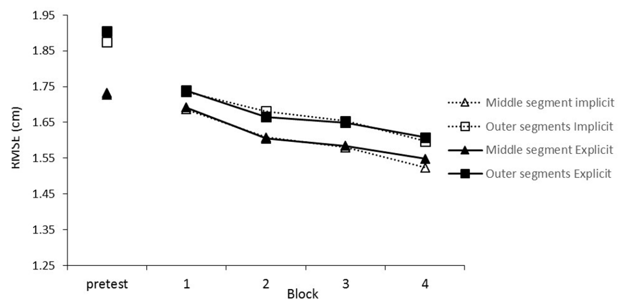

FIGURE 6 | Root mean square error scores for the training blocks. The pre-test, Block 1 and Block 2 were completed on 1 day, Block 3 and Block 4 were completed on another day.

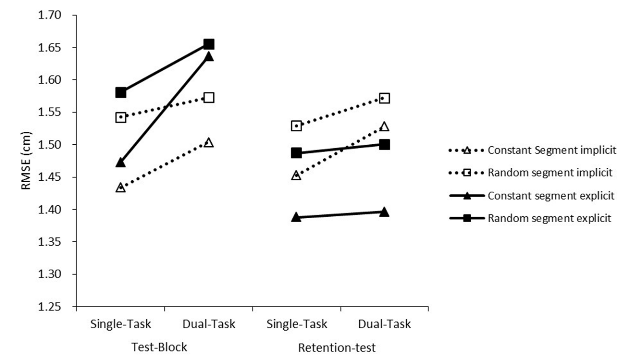

FIGURE 7 | Root mean square error scores for the test-block and the retention test performed 1 week later.

system aids the performance of the implicit system (Reber et al., 1980; Berry and Dienes, 1993). As in the first experiment we do not expect effects of predictability to carry over to the reaction time task, dual-task training would in fact more likely serve to uncouple the two unrelated tasks in order to process them more efficiently, in accordance with the Integrated Task Processing concept of Manzey (1993).

Materials and Methods

Participants

The implicit group contained 19 participants (M = 24.0 years old, SD = 2.5) and the explicit group had 20 participants (M = 23.76 years old, SD = 2.44). All participants had normal or corrected-to-normal vision and no reported neurological disorders. All participants gave informed consent prior to the start of the experiment and received remuneration of 20€ or course credit after completing the experiment. The research was approved by the local ethics committee of the University of Augsburg. Experiment setup, task and display were identical to Experiment 1.

Procedure

The procedure of Experiment 2 differed from Experiment 1 in that participants performed the training of the tracking task always together with the auditory reaction time task (see **Figure 5** for the complete protocol). The pre-test included single task and dual-task trials. Participants were asked to try their best on both tasks equally throughout the experiment. Another difference with Experiment 1 is that the training blocks contained 20 trials instead of the 40 trials because we found in a pilot that fatigue played a much larger role in the dual-task training than the single task training. Furthermore, the test-block was expanded to contain both testing under single and dual task conditions. Lastly, a retention test was done on a third day, a week after the test-block was performed. The retention test was exactly the same as the test-block and was added to see if learning was consolidated and test performance without the possibly confounding effect of fatigue resulting from putting the test-block at the end of multiple training blocks.

Data Analyses

To test learning effects during the training blocks we submitted RMSE scores to a 4 × 2 × 2 mixed analysis of variance (ANOVA) with within subjects factors Training Block (four training blocks), Segment (repeated middle segment vs. outer segments), and between subjects factors Group (implicit vs. explicit). To analyze test-block and retention test performance on a learned middle segment against performance on a random segment for dual or single-task conditions we had the choice to either compare the repeated middle segment with a random middle segment or to compare the repeated middle segment with the random outer segments. Since the data suggested that segment position might be a confounder, with better scores on the middle segment during the pre-test (see **Figure 6**), we chose the first option and analyzed RMSE scores with a 2 × 2 × 2 × 2 ANOVA with within-subjects factors Test (test-block vs. retention test), Segment (Constant vs. Random, both in the middle), Condition (Single-task vs. Dual-task) and between-subjects factor Group (Implicit vs. Explicit). Similarly we submitted reaction times to a 2 × 2 × 2 ANOVA with within-subjects factors Test, Condition (Repeating segment in the middle vs. Random segment in the middle) and Group. To check for the existence of dual-task costs during the test-block and retention test we performed another 2 × 2 × 2 ANOVA with within-subjects factors Test (Test-block vs. Retention test), Condition (Dual-task with repeating segment in the middle vs. Single-task) and Group.

Results

The questionnaires revealed that one participant in the implicit group discovered the repeating middle segment, this data was removed from analyses.

During the training blocks participants improved, $F(1.57,58.05) = 7.21$, $p = 0.003$, $\eta_p^2 = 0.16$, and performance on the repeated segment was better than on the random segments, $F(1,37) = 11.45$, $p = 0.002$, $\eta_p^2 = 0.24$, but crucially we could not demonstrate an interaction effect between Block and Segment, $F(2.19,80.98) < 1$, $p = 0.672$, indicating that learning of the repeating segment was not better than learning of the random segments, see **Figure 6**. No difference between the implicit and explicit group could be found, $F(1,37) < 1$, $p = 0.972$.

In the test-block and retention test, see **Figure 7**, we found better tracking of a constant segment, $F(1,36) = 10.61$, $p = 0.002$, $\eta_p^2 = 0.228$. No significant dual-task costs could be found although it almost reached significance, $F(1,36) = 3.36$, $p = 0.075$. We did not find a significant interaction between Condition (dual-task vs. single-task) and Segment (constant vs. random), $F(1,36) = 1.65$, $p = 0.207$. No difference between the implicit and explicit group could be found, $F(1,36) < 1$, $p = 0.97$. There was a significant interaction effect of Test and Group (test-block vs. retention test), $F(1,36) = 4.21$, $p < 0.048$, $\eta_p^2 = 0.11$, indicating that the explicit group improved from test-block to retention-test while the implicit group did not.

No difference in reaction times between the repeating segment (M = 538 ms, SD = 69) and random segment was found (M = 538 ms, SD = 72), $F(1,36) = 3.28$, $p = 0.083$, nor was there a difference between the implicit (M = 531 ms, SD = 69) and explicit group (M = 554 ms, SD = 73), $F(1,37) = 1.39$, $p = 0.246$. We did find better performance on the retention-test (M = 527 ms, SD = 66) compared to the test-block performed earlier (M = 557 ms, SD = 76), $F(1,36) = 16.31$, $p < 0.001$, $\eta_p^2 = 0.312$. Dual-task costs were still present at the test-block and retention test when comparing dual-task performance on the repeated segment (M = 538 ms, SD = 69) with single task performance (M = 482 ms, SD = 57), $F(1,36) = 57.19$, $p < 0.001$, $\eta_p^2 = 0.614$. Moreover, a significant interaction effect between Condition and Group, $F(1,36) = 5.90$, $p = 0.020$, $\eta_p^2 = 0.141$, indicated that the difference in reaction times between Dual-task with a repeating segment and Single-task was greater for the explicit group (M = 76 ms, SE = 8) than the implicit group (M = 39 ms, SE = 13).

Discussion

For the second experiment we did not find learning due to repetition of the repeated middle segment during the training blocks, but we did see better performance on a repeated middle segment compared to the random middle segment during the test-block. These results concur with Frensch et al. (1998) in that a secondary task does not prevent learning, rather the expression of what is learned is suppressed. Although not significant, there seems to be some indication that explicit instructions hamper performance during dual-tasking more than no instructions, see **Figure 7**. This raises the question what the content of the learned information was for the explicit group. In the current experiment we cannot say whether the explicit group made use of explicit knowledge or that for them implicit knowledge was also helpful, whereas the interviews clearly prove that the implicit group did not make use of explicit knowledge. In other words, the results for the explicit group are consistent with the view that explicit knowledge is helpful for learning but the expression is suppressed during dual-tasking. But the results also concur with the view that only *implicit* learning occurs under dual-task conditions and that the explicit group in the current study acquired implicit knowledge in addition to the in dual-task situations harmful explicit knowledge.

The explicit group improved their tracking performance from the test-block to the retention test seemingly beyond that of the implicit group, whose performance remained the same. There is some evidence that the explicit memory system might inform or stimulate the implicit learning system (Reber et al., 1980; Willingham, 1999), although the contrasting view that explicit knowledge, especially instruction on how to perform movements, is also often found to be detrimental to the formation of motor skills (Poldrack and Packard, 2003). Our results are compatible with both these views since we did not give explicit instructions on how to perform the tracking movements, rather the explicit instructions more likely had the effect of focusing attention to the repeating segment aiding implicit learning.

As in the Experiment 1 reaction times did not decrease during the predictable tracking segment, possibly a sign of effective task shielding, a concept closely related to the Integrated Task Processing concept of Manzey (1993) introduced earlier, which states that training two tasks together should enable participants to uncouple them, therefore reducing interference and improving dual-task performance. Task shielding is useful to protect a primary task from distractors but might also lead to less cognitive flexibility, so that the predictability of the tracking task in our study could not be exploited for the reaction time task (Plessow et al., 2011, 2012). If the strategy during the current experiment was to decouple the tasks there is no reason to assume that predictability of one task influences performance on the other task. The influence the two tasks might have on each other, for better or worse, is exactly what participants learned to avoid. Another explanation is that predictability does not transfer between modalities, in line with the idea of multiple resources. The visual-manual system may not share resources with the auditory-pedal system and a reduction of resource usage for predictability does not help the other system.

GENERAL DISCUSSION

The finding of both experiments suggests there is a beneficial but limited role of predictability in multitasking performance. Our task differs from the SRT task used in similar investigation but there seems to be converging evidence that in dual-task situations explicit knowledge of a sequence is not as beneficial as implicitly learned movement sequences (Heuer and Schmidtke, 1996; Frensch et al., 1998). Although the effect was not statistically significant, our results agree with this: after single-task training both explicitly instructed and implicitly trained participants performed better on predictable segments of the tracking segment whereas after dual-task training, *initially* only the implicit group demonstrated learning effects in the dual-task condition. However, when tested again a week later the explicit group demonstrated similar learning effects and a larger overall improvement in performance compared to the implicit group. A possible explanation is that explicit instructions aid implicit motor learning but initially interfere with the expression of knowledge. Another explanation is that explicit instructions fatigued the participants more, the test-block was performed after two training blocks while the retention test was performed on a different day without any training blocks.

The fact that we found learning after dual-task training is in contrast with the hypothesis of Nissen and Bullemer (1987) who argued that learning may occur without awareness but always requires attention, following from their findings that no learning was found when combining the SRT task with a secondary task. Since then this view has been sharpened by results from Cohen et al. (1990) and Curran and Keele (1993) who found evidence that unique sequences, where each item is always uniquely followed by a certain other item, can be learned in the presence of attentional distraction, whereas sequences that lacked such an item to item connection could not. As such our findings are in agreement with the idea of a non-attentional and an attentional learning system, either with or without awareness.

A limitation of the current study is that while we tested for the absence of explicit knowledge in the implicit group we did not confirm the existence of explicit knowledge in explicit group. Future studies should employ methods to test how explicit knowledge of the repeating segment is stored, reproducing or identifying the repeating segment might be more suitable methods of assessing explicit knowledge than describing the curve. Furthermore, a comparison with an implicit group would be necessary because these methods cannot completely distinguish between implicit and explicit knowledge (Chambaron et al., 2006).

CONCLUSION

Predictability through knowledge aids dual-task performance, which can be explained by different learning mechanisms. In dual-task training explicit instructions seem to initially worsen performance, possibly because of fatigue, but ultimately they lead to better consolidation of motor learning. The other main finding is that predictability of one task does not increase performance in the other task. Future research will focus on further elucidating the role of predictability in dual-task performance by investigating the effect of making each task predictable, for instance making the auditory reaction time task be a constant sequence, or by making both tasks predictable as a unit, facilitating task integration and countering task-shielding. The latter avenue of research is intriguing because it challenges us to think about what a 'task' is: can performing two integrated tasks still be seen as dual-tasking (Künzell et al., 2017). Although difficult to access and likely dependent on individual differences, it may be possible to present task boundaries in such a way that the manner in which two tasks are conceptualized facilitates multitasking performance, possibly through manipulation of instructions or feedback (Dreisbach et al., 2007; Freedberg et al., 2014; Bröker et al., 2017).

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the ethical guidelines of the ethics committee of the University of Augsburg. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Augsburg University.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

This research was supported by a grant within the Priority Program, SPP 1772 from the German Research Foundation [Deutsche Forschungsgemeinschaft (DFG)], grant nos. KU 1557/3-1 and RA 940/17-1.

ACKNOWLEDGMENT

The authors would like to thank Bettina Rathke and Isabella Schedel for helping with data collection.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

OPINION
published: 22 November 2017
doi: 10.3389/fpsyg.2017.02021

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Why Prediction Matters in Multitasking and How Predictability Can Improve It

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Keywords: prediction, predictability, multitasking, multitasking performance, sources of predictability

Edited by:
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Specialty section:
This article was submitted to
Movement Science and Sport
Psychology,
a section of the journal
Frontiers in Psychology

Received: 08 September 2017
Accepted: 06 November 2017
Published: 22 November 2017

Citation:
Broeker L, Kiesel A, Aufschnaiter S,
Ewolds HE, Gaschler R, Haider H,
Künzell S, Raab M, Röttger E,
Thomaschke R and Zhao F (2017)
Why Prediction Matters in Multitasking
and How Predictability Can Improve It.
Front. Psychol. 8:2021.
doi: 10.3389/fpsyg.2017.02021

Prediction[1] is an omnipresent principle of human behavior that can be fostered by predictability in the environment. We regard prediction as the mental representation of future event states or anticipated action consequences, and predictability as a property of certain events in the environment. On the assumption that predictability and prediction are beneficial for any kind of behavior, we argue that their benefits to relieving the human system are most evident when encountering *multiple* tasks. However, we predicate that their impact on multitasking is understudied and so we aim at dissociating prediction and predictability within multitasking contexts and at outlining different sources of predictability that have not been conflated under this term so far. From our opinion it follows that future multitasking research requires experimental designs and analyses that consider and unveil principles of prediction and the impact of predictability on multitasking performance.

OMNIPRESENCE OF PREDICTION ACCORDING TO PREDICTIVE CODING PRINCIPLES

Blakemore et al. (2000) proposed that it is impossible to tickle oneself, because there is no difference between predicted sensory consequences of one's forward model and the actually experienced sensory consequences. This means that there is entirely no surprise, which is tantamount to a prediction error of zero. In a general sense, people predict the effect of an action without necessarily being aware of it (Wolpert et al., 2003), and, according to ideomotor theory, also initiate voluntary actions by the prediction of their effects.

Neurosciences have encouraged the idea of interpreting the cognitive system as a predictive coding machine, with the brain being seen as an anticipation device or feedforward processing machine (Bubic et al., 2010). Likewise, Friston (2010) has proposed the *free energy principle*, arguing that organisms try to counteract disorder by avoiding surprise (minimizing free energy). According to this principle, our internal states represent what has most likely caused a sensation, and we do not only try to evaluate these hypotheses in the external world, but permanently update them depending on the extent of the prediction error. The better the fit between internal and external state, the lower the free energy (Clark, 2013). The most important implication is that organisms

[1] Prediction is equated with *anticipation* and *expectation* (Northoff, 2014, p. 146).

have no need to search for regularities in the environment, but rather automatically adapt to them as a consequence of the continuous updating of representations about the external world due to the prediction error. Independent of specific models across disciplines, there is some agreement that these predictions are made outside of awareness, and we only become aware of them when they are violated and feelings of surprise draw attention to them (Whittlesea, 2004). However, it has been suggested that conscious predictions occur concurrently and independent from unaware predictions (Perruchet et al., 2006).

Accepting prediction as a permanently ongoing process of the cognitive and motor system, plus accepting multitasking as intrinsic part of both systems, implies that prediction should also leave its traces on multitasking. Multitasking paradigms, as typical testbeds for the capabilities and limits of motor-cognitive interaction, should therefore be eminently suitable to showcase that prediction and predictability matters for performance. For instance, prediction errors cannot decrease when different tasks are paired at random, when tasks are unpredictably sequenced or when different probabilities violate expectations about upcoming tasks. In contrast, predictability in task-environments, allowing people to develop predictions about tasks, stimuli or motor requirements, attenuate prediction errors, and ameliorate multitasking performance, which we will exemplify below.

SOURCES OF PREDICTABILITY IN MULTITASKING SETTINGS

Multitasking refers to task requirements in which cognitive processes involved in performing two (or more) tasks overlap in time, and it is typically investigated in dual-task or task-switching paradigms. Usually, multitasking is related to performance costs that manifest in increased reaction times for the second task or task switches and have for instance been explained by structural bottlenecks or the exhaustion of overall capacity limits (for overviews see Kiesel et al., 2010; Fischer and Plessow, 2015). Besides examining multitasking costs, one endeavor of multitasking research is the identification of sources fostering interference-reduction. We suggest that one major contributor to this is predictability in its various forms.

SEQUENTIAL STRUCTURES

Dual-task studies suggest that people automatically use events (i.e., stimuli/responses) in one task to predict events in the other task (Jiménez and Méndez, 2001). While automatic prediction of elements in Task-A, based on elements in Task-B, disrupts sequence learning when one task is random, fast reactions and implicit sequence learning are preserved when stimuli and responses in both tasks are arranged such that predictive relationships between task elements hold (Keele et al., 2003; Röttger et al., 2017). In general, results from dual-task sequence learning studies suggest that prediction occurs automatically and is per default not depending on task boundaries.

Similarly, task switching studies suggest that people can acquire *implicit* knowledge about the sequences of *tasks* (Heuer et al., 2001; Koch, 2001). In task-switching setups where, unbeknownst to participants, tasks follow a regularly repeating sequence, participants respond faster as compared to baseline conditions where tasks switch randomly. Presumably, automatic prediction based on implicit task-sequence knowledge fosters the preparation of the upcoming task set.

TIME CONTINGENCY

Other than enhancing predictability by structuring events or tasks, recent accounts have investigated the impact of interval durations between tasks, assuming that the temporal distribution of tasks may carry information about which task will occur. To investigate whether participants adapt to regularities of waiting time and task requirements, Aufschnaiter et al. (2017) employed a setting in which inter-task delays predicted the task type in the upcoming trial with different probabilities (70, 80, and 90%). Participants responded faster to frequent than to infrequent delay-task combinations for all tested degrees of predictability and both, task switches and repetitions, benefited from the predictability of time to task. Again, there is evidence for the omnipresence of prediction, as participants did not become aware of the predictive value of the interval duration.

EXPLICIT CUES

In contrast to implicit predictability based on sequences or time, other studies manipulated predictability by providing *explicit* task cues that precede the imperative target stimuli (Meiran, 1996). Typically, these studies manipulate the duration of the interval between cue and imperative stimulus to investigate processes of task preparation (Kiesel et al., 2010), hypothesizing that longer preparation equals better prediction. They provide accumulative evidence that prolonging cue-stimulus intervals leads to reduced switch costs, indicating that switches benefit more from longer preparation times than repetitions (Logan and Bundesen, 2004), and that this effect is even more pronounced when additional cues are provided during preparation time (Koch, 2003).

Some studies also manipulated validity of explicit cues. In most studies, the cue predicts the task deterministically (100% valid), and any cue-based preparation will always be correct. However, in real life multitasking, cues often involve some degree of uncertainty, predicting tasks only probabilistically. Those few studies employing probabilistic cues observed preparation in terms of better performance for valid than invalid trials (Dreisbach et al., 2002; Wendt et al., 2012). Yet, results are inconclusive regarding preparation effects in switch and repetition trials (Dreisbach et al., 2002) vs. switch trials only (Wendt et al., 2012).

SENSORIMOTOR CUES

In addition to external cues that precede the imperative stimulus, the system itself is capable of providing predictive sensorimotor cues *prior* to executing an action. Sensory signals and motor commands both provide useful information to reinforce internal forward models, capturing the causal link between actions and their sensory consequences. So, relevant sensorimotor cues would be internal predictions based on efference copies of motor commands (Synofzik et al., 2013). In dual-task tracking studies either the middle segment of the tracking path was repeated or participants were provided with visual guidance information. Both, implicit motor learning of the middle segment and the exploitation of visual information through feed forward control, improved tracking performance even in the presence of a secondary auditory detection task and independent of participants' awareness (Ewolds et al., submitted). Wolpert and Flanagan (2001) suggested that predictive control mechanisms can be best exploited when the environment is predictable, but that sensorimotor cues are the most useful signal for the system whenever the environment is unpredictable.

PREDICTION IN UNPREDICTABLE CONTEXTS

In accordance with predictive coding, prediction is an ongoing process independent of predictability in the environment, and people seem to indeed predict upcoming trials even for random task and stimulus distributions. For instance, in sequence-learning experiments where tasks were drawn at random but participants were forced to predict the upcoming task, predicted tasks were performed faster than upcoming tasks not fulfilling the prediction (Gaschler et al., 2014). Likewise, task switching experiments revealed that participants respond faster to stimulus repetitions in repetition trials compared to repetitions in switch trials (Altmann, 2011). This effect has recently been ascribed to a "priming and inhibition" account (Druey, 2014), assuming that after response activation the corresponding response category is always inhibited, which leads to slower responses for repetitions in switch trials. Only if a stimulus in a specific task-set is repeated, there is an additional priming of the stimulus category, which outweighs the response inhibition, and enables participants to respond faster to stimulus repetitions than stimulus switches in repetition trials.

Furthermore, results of cued task-switching studies by Horoufchin et al. (2011a,b) demonstrate that participants predict repetitions of time structures in consecutive trials. The authors manipulated the duration of response-to-cue-intervals (RCI) in switch and repetition trials, and analyzed the effects of short and long RCI depending on whether they changed from the previous trial. They observed that participants responded faster in repetition trials compared to switch trials, and that this repetition advantage was of similar size for short and long RCIs when the RCI from the previous trial repeated. If, however, the RCI from the previous trial changed, the advantage of task repetitions decreased and switch costs increased. The overall results (especially the lack of RCI effects with unchanged RCI) were explained by a temporal distinctiveness account on episodic retrieval, which presumes that if a similar temporal relation between the previous and the current RCI exists, task episode of the previous trial can be retrieved in the current trial and repetition advantages unfold.

PROSPECTS

As outlined throughout the text, we presuppose automatic prediction of cues, tasks and stimuli or required responses, and hope to have convincingly conveyed that prediction and predictability matter for multitasking performance. Yet, multitasking studies often either ignore the impact of prediction or lack a measurement of it, and it is often hard to identify (and evaluate the role of) trials in which predictions mismatch the cue and the upcoming task. Thus, a consequence of this opinion would not only be the consideration of the system's predictive nature when conducting multitasking experiments, but the requirement to change analyses and research designs beyond core performance measures that capture prediction in multitasking behavior. We suggest that one way to realize this could be the implementation of more trial-wise analyses, because aggregating data over many trials might conceal the (incremental) impact of predictions. This might be especially important for settings that require learning or operate with predictions of varying validity. Further, reinforcing additional measures like error negativity/positivity would extend classic measures like reaction times (Alexander and Brown, 2011), which rather capture after-effects of valid or invalid predictions and do not adequately reflect core processing of prediction that occurs prior to stimulus presentation. Taking account of invalid predictions (e.g., by considering post-error slowing), would further lead to more nuanced understanding of performance differences. Other than that, it could be useful to consider people's awareness about predictions. Although we presuppose automatic prediction, there is evidence that making people realize the automaticity of predictions and actions may lead to deterioration of performance. For instance, Beilock et al. (2002) showed that multitasking performance in golf experts suffered when they had to pay attention to the step-by-step execution of putting, and attributed this to the intrusion into automatic processes that ground on well-developed forward models and predictions about future results of one's action.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication

FUNDING

This research was supported by the Deutsche Forschungsgemeinschaft (DFG; grant no. RA 940/17-1; KI 1388/7-1; TH 1554/3-1, KU 1557/3-1; HA 5447/11-1, GA 2246/1-1) in the context of the DFG Priority Program 1772 on "Human performance under multiple cognitive task requirements: From basic mechanisms to optimized task scheduling."

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