

# The Functional Role of Working Memory in the (Re-)Planning and Execution of Grasping Movements

M. A. Spiegel, D. Koester, and T. Schack  
Bielefeld University

Three experiments were conducted to dissociate movement planning costs and movement execution costs in working memory (WM). The aim of the study was to clarify what kind of WM processes (verbal, spatial, or both) are recruited during movement planning and movement execution. Therefore, a WM task (verbal and spatial versions) was combined with a high-precision manual action. Participants initially planned a placing movement toward 1 of 2 targets, subsequently encoded verbal or spatial information in WM, and then executed the movement during the retention phase. We tested the impact of movement execution on memory performance (Experiment 1), the role of WM task difficulty as a moderating variable in motor–memory interactions (Experiment 2), and the impact of implementing a new motor plan during memory retention (Experiment 3). Our results show that movement execution disrupted spatial more than verbal memory (Experiment 1) and that this domain-specific interference pattern was independent of WM task difficulty (Experiment 2). Hence, the results of Experiments 1 and 2 demonstrate that executing a prepared movement recruits domain-specific visuospatial memory resources. Experiment 3 involved trials that required the implementation of a new motor plan. The additional planning requirement during the retention phase reduced performance in both WM tasks in equal measure beyond the relative movement execution costs observed in Experiments 1 and 2. These results provide evidence for distinct roles of WM in manual actions, with action execution requiring principally modality-specific capacities and (re-)planning engaging modality-general WM resources.

**Keywords:** goal-directed action, interference, domain-specificity, action modification, working memory

In our everyday life, we are continuously planning, executing, and if necessary, adjusting our motor decisions. Movement planning and movement control are commonly considered as two functionally distinct components of goal-directed actions (Elliott, Helsen, & Chua, 2001; Jeannerod, 1984b; Woodworth, 1899; for a review, see Glover, 2004). The two components can be regarded as two stages of a problem-solving process: Planning requires the predetermination of a course of action aimed at achieving a goal, and control entails monitoring and guiding the execution of a plan to a useful conclusion (Hayes-Roth & Hayes-Roth, 1979). Movement planning occurs prior to movement execution and processes general, goal-relevant information, for example, goal determination, movement direction, effector and target selection, metrical

properties of the target, and analysis of object affordances, each of which is necessary to initiate a successful movement (cf. Glover, Wall, & Smith, 2012; Hommel, 2003). Hence, planning an action can be regarded as a process that occurs in advance and offline. In contrast, during movement execution, monitoring and fine tuning of the movement are accomplished by online control processes via feedback cycles (Glover et al., 2012; Jeannerod, 1984a; Wolpert & Ghahramani, 2000). However, when unexpected changes in the environment occur, we have to quickly adapt our previously made action decisions. Flexible movement adjustments may require either the replacement of the initial movement plan with another plan or a modification of the initial plan with respect to one or more parameters such as, for example, increasing movement speed (cf. Quinn & Sherwood, 1983).

Because the study of how decisions are enacted has received little attention in psychology (cf. Rosenbaum, 2005), the role of working memory (WM) involvement in the planning and execution of complex movements, especially with respect to action replanning, is not yet clear. Therefore, the present study explored the recruitment of WM processes (a) during the execution including the monitoring of a prepared manual action and (b) during corrective replanning of the movement direction in a goal-directed object-placing movement.

Memory and action have a close functional relationship. WM typically refers to the cognitive processes involved in the temporary storage and manipulation of information (Baddeley, 1992). During movement planning, memory representations play a central role in holding goal-relevant information active in WM to subsequently convert it into a movement program (Ohbayashi, Ohki, &

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M. A. Spiegel, D. Koester, and T. Schack, Neurocognition and Action—Biomechanics Research Group, Bielefeld University, Bielefeld, Germany, and Center of Excellence—Cognitive Interaction Technology (CITEC), Bielefeld University.

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Correspondence concerning this article should be addressed to Marnie A. Spiegel, Neurocognition and Action—Biomechanics Research Group, Faculty of Psychology and Sport Sciences, Bielefeld University, Room N3-101, 33501 Bielefeld, Germany. E-mail: mspiegel@cit-ec.uni-bielefeld.de

Miyashita, 2003). The cognitive representation of a forthcoming movement was shown to include considerable details about movement starts and ends, such as, for example, target distance and width (Rosenbaum, Halloran, & Cohen, 2006), the desired hand location, and forearm orientation (Herbort & Butz, 2010). Accordingly, executing grasping movements after a delay has been shown to be memory-guided (Hesse & Franz, 2009, 2010). Regarding the involvement of WM processes during action execution, Miller, Galanter, and Pribram (1960), who originally suggested the term *working memory*, state in their seminal book *Plans and the Structure of Behavior*,

When we have decided to execute some particular Plan, it is probably put into some special state or place where it can be remembered while it is being executed. . . . Without committing ourselves to any specific machinery, therefore, we should like to speak of the memory we use for the execution of our Plans as a kind of quick-access, "working memory." (cf. Miller et al., 1960, p. 65)

Hence, WM processes seem to be employed during action execution. Accordingly, disruptive effects of concurrent movements on memory performance have been reported for tasks such as pointing (Hale, Myerson, Rhee, Weiss, & Abrams, 1996), finger tapping (Bathurst & Kee, 1994; Smyth, Pearson, & Pendleton, 1988), arm movements (Kirsch, Hennighausen, & Rösler, 2009; Lawrence, Myerson, Oonk, & Abrams, 2001; Quinn & Ralston, 1986), eye movements (Lawrence et al., 2001; Postle, Idzikowski, Della Sala, Logie, & Baddeley, 2006), and more complex everyday life tasks (Weigelt, Rosenbaum, Huelshorst, & Schack, 2009). For example, Lawrence et al. (2001) compared the effects of different types of spatially directed movements (i.e., reflexive saccades, symbolically cued prosaccades, antisaccades, and limb movements) that were performed during the retention interval between memory encoding and memory retrieval. Their results show that all these movements disrupted WM performance. A recent study by Logan and Fischman (2011) demonstrated that motor activity that involved no or only very limited motor planning produced interference effects with the short-term storage of information. The authors interpreted this finding as the *basic concurrence costs* of physical action, suggesting that the mere execution of a motor task may result in performance deterioration in concurrent memory tasks. However, to our knowledge, it has not been investigated which performance costs in WM are due to simultaneously performing a manual action (*execution costs*) and which performance costs are due to additional planning requirements (*replanning costs*).

In cognitive psychology, little research has focused on the costs of replanning an intended action. We define *replanning* as movement planning processes that are required after movement initiation because one or more goal parameters (e.g., movement direction) have changed, and thus the initial movement plan would not satisfy the intended action goal. In the field of motor control, researchers have commonly studied the kinematic characteristics of adaptive responses by experimentally changing extrinsic (e.g., the spatial location of objects) or intrinsic (e.g., shape and size) objects properties shortly before or at grasp onset (e.g., Castiello, Bennett, & Chambers, 1998; Castiello, Bennett, & Stelmach, 1993; Desmurget et al., 1996; Gentilucci, Chieffi, Scarpa, & Castiello, 1992; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). For cor-

rective movement adjustments, it has been shown that, in accomplishing the new action goal, individuals plan the adapted grasp posture to afford comfort at the end of the movement (Hughes et al., 2012). A recent study by Spiegel, Koester, Weigelt, and Schack (2012) provided first evidence that movement planning requirements during the retention phase of a WM task can specifically influence WM performance. In this study, replanning high-precision movements resulted in greater dual-task costs, that is, greater reduction in memory performance than replanning low-precision movements. In addition, by experimentally dissociating the movement planning from the control phase, the authors localized the main source of action-memory interactions to the planning phase. These results are compatible with those reported by Weigelt et al. (2009), who found that abandoning a selected grasping plan in favor of another (i.e., changing from overhand to underhand grasps or vice versa) disrupted the short-term storage of verbal information. However, the movement control component can contribute a unique source of interference, as suggested by Logan and Fischman (2011).

Critically, interference in WM may depend on the type of stored information (verbal vs. spatial), as would be reflected in domain-specific interference. Correspondingly, one of the most influential models of the cognitive architecture of WM, the *multicomponent model* (Baddeley & Hitch, 1974), comprises four specialized core components: two subsidiary domain-specific short-term stores; a central executive, which is an attentional control system of limited capacity; and an episodic buffer, which integrates information from both short-term stores and long-term memory (Baddeley, 1986, 2000; Baddeley & Hitch, 1974). One domain-specific short-term store, the visuospatial sketchpad, is capable of holding and manipulating information of a visual or spatial nature. The visuospatial sketchpad is assumed to function as an interface between visual and spatial information, accessed either through the senses or from long-term memory (Baddeley, 2001). The other short-term store, the phonological loop, is responsible for storing and rehearsing auditory-verbal information. It is assumed that both subsystems include a passive perceptual store and an active rehearsal mechanism for refreshing the specific content of the buffer. The verbal WM subsystem seems to comprise a perceptual phonological store, which can hold information for a few seconds, and an articulatory rehearsal process, which prevents memory traces from decaying by retrieving and rearticulating the information (cf. Baddeley, 2003). Accordingly, the spatial WM subsystem seems to include a passive visual store, the visual cache, rehearsed by an active store, the inner scribe (Logie, 1995). Rehearsal processes within the visuospatial sketchpad have been associated with oculomotor control processes (e.g., Baddeley, 1986; Pearson & Sahraie, 2003; Theeuwes, Olivers, & Chizk, 2005) as well as shifts of attention (e.g., Awh, Anillo-Vento, & Hillyard, 2000; Awh & Jonides, 2001; Awh, Jonides, & Reuter-Lorenz, 1998; Postle, Awh, Jonides, Smith, & D'Esposito, 2004; Smyth & Scholey, 1994). Although, the exact role of attention as a rehearsal mechanism in spatial WM is not yet clear (e.g., Belopolsky & Theeuwes, 2009; Chan, Hayward, & Theeuwes, 2009; Klauer & Stegmaier, 1997), the empirical findings suggest that spatial WM shares important resources with spatial attention and oculomotor control (Repovs & Baddeley, 2006).

The concept of domain-specific resources has been extensively discussed in the WM literature (e.g., Baddeley, 1996b; Cocchini,

Logie, Della Sala, MacPherson, & Baddeley, 2002; D'Esposito et al., 1998; Gruber & von Cramon, 2003; McEvoy, Smith, & Gevins, 1998; Miyake & Shah, 1999; Smith, Jonides, & Koeppel, 1996). Performance dissociations between verbal and spatial WM have been reported for patients (e.g., Hanley, Young, & Pearson, 1991; Lang & Quitz, 2012; Ravizza, Behrmann, & Fiez, 2005), children (e.g., Alloway, Gathercole, & Pickering, 2006; Lambek & Shevlin, 2011), and healthy adults (e.g., Cocchini et al., 2002; Farmer, Berman, & Fletcher, 1986; Lawrence, Myerson, & Abrams, 2004; Myerson, Hale, Rhee, & Jenkins, 1999; Smyth & Scholey, 1994). For example, Cocchini et al. (2002) demonstrated that verbal but not visual memory was disrupted by articulatory suppression interpolated between stimulus presentation and recall. Myerson et al. (1999) reported that color naming interfered with memory for digits, but not with memory for locations. Pointing to matching colors, in contrast, selectively interfered with memory for locations, leaving memory for digits unimpaired. Accordingly, eye movements have been shown to interfere with spatial but not verbal WM (Lawrence et al., 2004). Functional neuroanatomical studies further suggest that verbal and spatial WM components are represented by different domain-specific cortical networks (e.g., Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; Gruber & von Cramon, 2003; Jonides et al., 1993; Paulesu, Frith, & Frackowiak, 1993). Based on these results, it appears that short-term memory storage and processing is sensitive to domain-specific information.

The present research aims to contribute to the question of whether the two components of goal-directed actions, movement planning and control, engage similar WM processes. There is a lack of evidence for the relative involvement of visual and spatial WM processes in the two movement phases. Does replanning a movement versus performing a movement in a planned direction result in similar interaction patterns with a simultaneous WM task? Accordingly, we explored whether or not movement execution costs (cf. Logan & Fischman, 2011) and movement planning costs (cf. Spiegel et al., 2012) originate from common sources of interference, resulting in similar patterns of interaction with information held active in WM. To our knowledge, this is the first study on movement-related costs that provides a comparative investigation of movement execution- and movement planning-associated WM costs.

The goals of the present study were threefold: First, we tested the basic concurrence costs hypothesis, namely that concurrent movement reduces performance in a simultaneous WM task. Second, we separated movement execution from planning costs by adding movement replanning requirements to the dual task. And third, we explored the domain-specificity (verbal or spatial) of both movement execution and replanning costs. To clarify, we sought to find out whether movement execution and replanning engage verbal and spatial WM capacities to a similar degree. Thus, Experiment 1 was designed to identify movement execution costs by comparing conditions in which a verbal and a spatial version of a WM task were performed without concurrent motor activity (single task) with conditions in which the WM task was embedded in a prepared goal-directed placing movement (dual task). Experiment 2 addressed the role of WM task difficulty in modulating movement execution costs. Therefore, Experiment 2 was identical to Experiment 1, with the exception that we used verbal and spatial WM tasks of low and high cognitive load to compare performance

in these WM tasks across single- and dual-task conditions. In contrast, Experiment 3 was designed to test whether movement execution costs and movement planning costs originate from similar or distinct sources of interference as would be reflected in the interference patterns with different types of information (verbal vs. spatial) temporarily stored in WM. To approach this question, we compared verbal and spatial memory performance in conditions in which participants could keep a prepared action plan with conditions in which the implementation of a new action plan was required.

## Experiment 1

The objective of Experiment 1 was to test the hypothesis that the parallel execution of a preplanned goal-directed placing movement creates execution costs in verbal and spatial WM tasks. Therefore, participants were tested in two task conditions: In the baseline single-task condition, participants consecutively performed a verbal (letter recall) and a spatial (recall of symbols positioned in a  $4 \times 4$  matrix) WM task. In the dual-task condition, each of the WM tasks was embedded in a grasp-to-place task. Subjects grasped a sphere and planned the successive placing movement toward one of two identical target positions. Subsequently, they encoded the verbal or the spatial information, executed the placing movement while maintaining the information in WM, and finally reported the letters or symbols.

We tested the movement concurrence costs hypothesis suggested by Logan and Fischman (2011), namely that simultaneous motor activity can deteriorate memory performance. The use of verbal and spatial WM conditions enabled us to separately evaluate the hypothesized negative effects of motor activity on memory performance. Accordingly, we expected that the concurrent motor activity would require cognitive resources that would interact with resources needed for the memory task. Hence, if movement execution-related costs are domain-specific, that is, motor activity differentially affects verbal and spatial information, we predicted a main effect of task condition and an interaction between task condition and WM type on memory performance. Alternatively, we predicted only a main effect of task condition but no interaction if the execution costs are non-domain-specific. In contrast, an observation of similar memory performance in the single-task condition and the dual-task condition would support the null hypothesis and reject the assumption of movement execution costs on memory.

## Method

**Participants.** Twenty-four right-handed individuals (11 women, 13 men,  $M$  age = 24.7 years,  $SD$  = 3.4, range = 20–34 years) participated in exchange for either 5€ or 1 hr of participation credits. All participants reported normal or corrected-to-normal vision and were naïve with regard to the purpose of the study. Before giving their written informed consent, they were briefed on the nature of the experiment and the operating mode of the experimental setup.

**Apparatus and stimuli.** For the verbal WM task, 100 randomly chosen letter sequences were used, each consisting of eight distinct consonants of the Latin alphabet (each letter measured 2 cm in height and width). The letter string was presented along a

vertical axis centered in the middle of the screen. Aligning the letters along the vertical axis ensured that the stimuli would not be subject to spatial effects. The sequences did not contain abbreviations, alphabetic orders were avoided (e.g., *C*, *D*), and the frequency in which each letter occurred was controlled. The  $4 \times 4$  symbol matrices used in the spatial WM task contained eight symbols (triangles, dots, or squares), each measuring 2 cm in height and width. The symbols were presented at eight of 16 equiprobable positions of the matrix that appeared in the center of the screen. Using matrix patterns increased the likelihood that the information would be retained spatially rather than verbally because symbols cannot be exclusively verbalized or recoded by verbal rehearsal mechanisms (Rudkin, Pearson, & Logie, 2007; Wilson, Wiedmann, Hadley, & Brooks, 1989). Acoustic stimuli were a low (400 Hz) and a high (750 Hz) sinusoidal tone each of 500-ms duration.

The task board ( $4 \times 60 \times 28$  cm) for the grasp-to-place task included a starting position and two sticks (10 cm high, 0.5 cm wide) as motor targets. The targets were positioned on the left and right side of the work space, each 15 cm away from the center of the setup. The middle of the setup was marked by a yellow cross. All three positions were equipped with pressure-sensitive micro switches to allow self-paced trial beginnings and ends. The motor task was to fit a sphere (6 cm in diameter, furnished with a hole of 1 cm in diameter) according to a directional arrow ( $2.5 \times 1.5$  cm) onto one of the sticks.

**Procedure.** At the beginning of each trial, a fixation cross was displayed in the center of a 17-in. flat-screen monitor with integrated speakers. The sequence of stimulus events was the same in both the single-task condition and the dual-task condition (see Figure 1), although a different set of letter strings and symbol matrices was used to avoid repetition effects between both conditions.

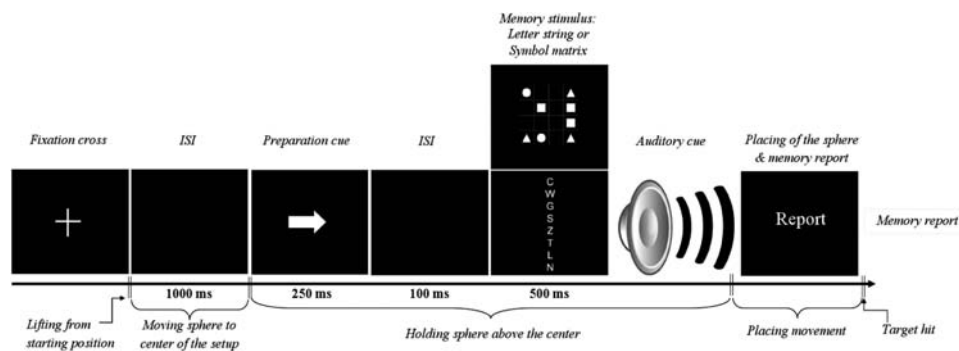
In the single-task condition, each trial was initiated and terminated by the experimenter via keyboard. Each trial consisted of a fixed sequence of stimulus events. The first stimulus was a directional arrow (left vs. right) presented for 250 ms. The arrow was either followed by a  $4 \times 4$  symbol matrix or a letter string (500 ms), depending on which WM domain was tested. The WM stimulus was followed by one of the two auditory cues (500 ms)

and finally the cue to recall (displayed until target hit). As there was no secondary motor task in the single-task condition, participants were instructed to ignore the arrow and the auditory cue. The response modality was vocal for the verbal WM task (saying the letters) and manual for the spatial task (drawing the symbols in a  $4 \times 4$  matrix). Participants were encouraged to memorize as many letters and symbols as possible. More specifically, for the verbal WM task, participants were instructed to recall the presented letters independent of serial location, whereas for the spatial task, the correct symbols had to be recalled in locations.

In the dual-task condition, the verbal and spatial versions of the WM task were combined with the grasp-to-place task. At the beginning of each trial, the sphere was placed on the starting position. Participants grasped the sphere and lifted it from the starting position, which triggered the presentation of the stimulus sequence. During the 1,000-ms interstimulus interval (ISI), participants transported the sphere above the center of the setup and held it at this position until they were cued to recall. The ISI was followed by the directional arrow that indicated the action goal of the trial (left vs. right target). Participants subsequently encoded the WM stimulus and then executed the placing movement according to the preparation cue as soon as they were cued to recall. Participants in this condition were instructed to ignore the auditory cue. Fitting the sphere onto the target stick terminated the trial. The response modality for the memory report was again vocal (verbal WM task) or manual (spatial WM task). Placing the sphere back on the starting position and then lifting it again initiated the next trial. Instructions did not prioritize one task over the other. Participants were encouraged to memorize as many WM items as possible and to move the sphere quickly but at a comfortable speed to the correct target.

As the dependent variable for the verbal WM task, memory performance was defined as the number of correctly reported letters, independent of their position within the sequence. For the spatial WM task, memory performance was defined as the number of symbols that were reported at their correct position within the presented matrix.

Prior to the experimental trials, participants completed 10 practice trials for familiarization. Testing stimuli used for training were not used during data collection. Stimulus presentation, response



**Figure 1.** Timing of the stimulus sequence for one trial. At the beginning of each trial, a fixation cross was presented. Either the experimenter (single task) or the lifting of the sphere from the starting position (dual task) initiated a fixed sequence of events: ISI = interstimulus interval, preparation cue, memory stimulus (verbal vs. spatial), auditory cue (high or low), and finally "Report" (cue to place the sphere on the correct target and recall the information).



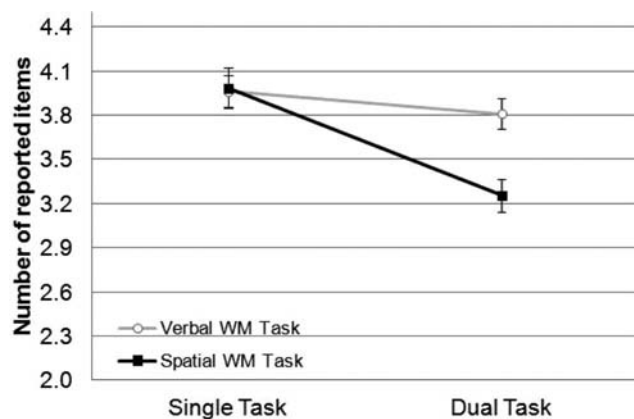


Figure 2. Mean memory performance in the verbal and spatial working memory (WM) tasks for the condition without movement (single task) and for the condition with a prepared placing movement (dual task) from Experiment 1, with error bars representing standard errors of the mean.

registration, and timing were controlled via Presentation software (Neurobehavioral Systems, Albany, CA). The entire experiment lasted approximately 60 min.

Experiment 1 rested on a  $2 \times 2$  within-subjects design with the factors task condition (single task vs. dual task) and WM domain (verbal vs. spatial). Each of the two task conditions consisted of a verbal and a spatial block with 50 trials each, resulting in a total of 200 experimental trials. Verbal and spatial blocks in the single and the dual task were separated by self-paced breaks. The order of presentation of the single task and dual task was counterbalanced and the WM stimuli were randomly presented. The auditory cues were counterbalanced across subjects.

## Results

In the single-task condition, mean memory performance was 3.97 letters ( $SD = 0.52$ ) in the verbal task and 3.98 symbols ( $SD = 0.68$ ) in the spatial task. Participants performed equally well in both WM single tasks,  $t(23) = 0.638$ ,  $p = .530$ , which indicates that both tasks were well matched for difficulty. To control that the order in which participants performed the verbal and spatial single-task and dual-task conditions, we included task order as an independent variable in the statistical analyses. A WM Domain (verbal vs. spatial)  $\times$  Task Condition (single task vs. dual task)  $\times$  Task Order (single task first vs. dual task first) analysis of variance (ANOVA) with repeated measures on WM domain and task condition was performed on memory performance, obtaining a significant interaction between WM domain and task condition,  $F(1, 20) = 38.555$ ,  $p < .001$ ,  $\eta_p^2 = .658$ . There was a significant main effect of task condition,  $F(1, 20) = 50.603$ ,  $p < .001$ ,  $\eta_p^2 = .717$ , but not of WM domain,  $F(1, 20) = 2.916$ ,  $p = .103$ ,  $\eta_p^2 = .127$ . Task order did not significantly influence memory performance ( $F < 1$ ). That is, as a consequence of the placing movement in the dual task, memory performance decreased compared with that in the single-task condition in both the verbal (3.81 items,  $SD = 0.51$ ),  $t(23) = 3.88$ ,  $p = .001$ , and the spatial WM tasks (3.25 items,  $SD = 0.56$ ),  $t(23) = 7.03$ ,  $p < .001$  (see Figure 2). Importantly, this performance drop induced by the secondary

motor task was more pronounced in the spatial compared with the verbal domain, as reflected in a significant difference between verbal and spatial memory performance in the dual-task condition,  $t(23) = 4.21$ ,  $p < .001$ .

## Discussion

The results of Experiment 1 show performance dissociation between verbal and spatial WM capacities induced by the concurrent placing movement. By comparing single-task performance (no movement) with dual-task performance (manual placing movement) in verbal and spatial WM tasks, we provide a method to measure movement execution costs in the verbal and spatial domains. Although participants in this study were not required to manipulate the stored information during retention, an operation that is often required in WM studies, the WM performance of about four items in the verbal and spatial single-task conditions appears to be in agreement with the assumption that both verbal and visuospatial WM are limited in capacity, typically to about three or four items (for a review, see Baddeley, 2003). Compared with the baseline single-task performance, the performance drop in the spatial WM task was more pronounced than that of the verbal WM task. These data suggest that the motor activity did not equally interfere with verbal and spatial information that was temporarily stored in WM. We interpret this finding as evidence for domain-specific execution costs on memory.

Importantly, the placing movements in Experiment 1 were prepared and required no additional planning processes during memory encoding. The execution of the placing movement during memory retention induced domain-specific movement execution costs in WM, suggesting that physical activity in and of itself occupies domain-specific WM capacities. Hence, the results of Experiment 1 confirm and extend the basic concurrence costs hypothesis (Logan & Fischman, 2011) by showing that movement execution costs were higher in the spatial as compared with the verbal domain. It seems that executing the prepared manual action recruited processing capacities that were also required for a spatial memory task. This competition for capacity-limited resources resulted in selective performance deterioration in the spatial WM task. By demonstrating execution-associated WM costs, Experiment 1 constitutes the basis for the comparative investigation of movement costs in WM. We then investigated planning-associated WM costs in Experiment 3.

However, before we approach the question of planning-associated costs in WM, let us consider a possible alternative explanation for the results of Experiment 1. Although single-task performance was comparable for the verbal and spatial task, one might still argue that the spatial task was more difficult than the verbal task. The spatial WM task required the participant to remember both the location and identity of the symbol, whereas the verbal task required the recall of letter identity only. It is conceivable that our participants compensated this potential difference in task difficulty by putting more effort into the spatial task. Such motivational compensation might have resulted in similar verbal and spatial single-task performance. The pronounced decrease of spatial WM performance in the dual task would then be an indication of a capacity limit due to the increased demands of the dual task rather than a domain-specific effect of movement execution on spatial WM. To address this alternative interpretation of the

data of Experiment 1, we manipulated task difficulty in Experiment 2.

## Experiment 2

Experiment 2 tested the hypothesis that differences in task difficulty between the verbal and spatial WM tasks caused the domain-specific interference with the concurrent execution of the manual placing movement. If the verbal WM task indeed required fewer resources than the spatial task, there might have been a sufficient amount of processing capacities left for the concurrent motor task, whereas the spatial WM task may have required more resources that movement control pulls away from. To approach this alternative explanation and uncover potential underlying differences in task difficulty between the WM tasks that might have been masked by equal single-task performance in Experiment 1, we manipulated task difficulty in Experiment 2. We compared single-task (no movement) performance with dual-task (manual placing movement) performance in easy and difficult versions of the verbal and spatial WM tasks.

If movement execution influences spatial WM rather than verbal WM, one would expect a decline in performance on both spatial tasks but not on the verbal tasks. In contrast, a decline in performance on the hard tasks but not the easy tasks (independent of the domain) would be more consistent with the deployment of a general pool of WM resources by movement control and not compatible with an interpretation of movement execution tapping domain-specific spatial WM resources.

## Method

**Participants.** Twenty-five right-handed individuals (14 women, 11 men,  $M$  age = 26.9 years,  $SD$  = 4.3, range = 20–38 years) were tested in individual 60-min sessions, receiving either course credit or 5€ as remuneration for participation. All participants reported normal or corrected-to-normal vision and were naïve about the purpose of the study. None of the participants in this experiment had participated in Experiment 1.

**Apparatus and stimuli.** For the verbal WM task, 120 randomly chosen letter sequences were used and the length of the letter string was manipulated to induce differences in task difficulty. Hence, half of the strings consisted of five (easy task) and the other half consisted of eight (difficult task) distinct consonants of the Latin alphabet. Correspondingly, for the spatial WM task, the number of presented symbols (triangles, dots, or squares) in the  $4 \times 4$  matrix was manipulated. Importantly, in designing and pretesting the stimuli, it became apparent that remembering five symbols in a  $4 \times 4$  matrix was more difficult than remembering eight symbols. It has been shown that both top-down and bottom-up perceptual features, for example, the subjective organization of the symbols into patterns and perceptual grouping, play an important role in the entry of information into WM (cf. Repovs & Baddeley, 2006; Schmidt, Vogel, Woodman, & Luck, 2002; Woodman, Vecera, & Luck, 2003; Xu, 2002). For example, Woodman et al. (2003) demonstrated that the perceptual organization of visual input, such as gestalt principles of proximity and connectedness, influence its transfer into visual WM. Hence, it appears to be more difficult to top-down organize five presented symbols in a  $4 \times 4$  matrix because each symbol has fewer

neighbors that can be used as spatial reference points. Consequently, the matrices containing five symbols were used as the difficult version of the spatial WM task and the matrices containing eight symbols were used as the easy task. To clarify, we did not seek to implement an equivalent manipulation between the verbal and spatial WM tasks but rather a difficulty manipulation within the verbal and spatial processing domain. With the exception of the manipulation of task difficulty, apparatus and stimuli in Experiment 2 were identical to Experiment 1.

**Procedure.** In the present experiment, the same general procedure used in Experiment 1 was employed. Again, participants were tested in a single-task (no movement) and a dual-task (manual placing movement) condition. A different set of letter strings and symbol matrices was used in each condition to avoid repetition effects. The sequence of stimulus events and experimental instructions were identical to Experiment 1.

Experiment 1 rested on a  $2 \times 2 \times 2$  within-subjects design with the factors task condition (single task vs. dual task), WM domain (verbal vs. spatial), and task difficulty (easy vs. difficult). Each of the two task conditions consisted of a verbal and a spatial block with 60 trials each (30 easy and 30 difficult), resulting in a total of 240 experimental trials. Verbal and spatial blocks in the single task and the dual task were separated by breaks. The order of presentation of the single task and dual task was counterbalanced and all WM stimuli (easy and difficult) were randomly presented.

## Results

In the single-task condition, mean memory performance in the verbal task was 4.2 letters ( $SD$  = 0.46), with 4.26 ( $SD$  = 0.46) in the easy version and 4.13 letters ( $SD$  = 0.48) in the difficult version. In the spatial task, mean memory performance was 3.89 symbols ( $SD$  = 0.83), with 4.27 ( $SD$  = 1.04) in the easy version and 3.51 symbols ( $SD$  = 0.67) in the difficult version. Overall, participants performed equally well in both versions of the WM single tasks,  $t(24) = 1.947$ ,  $p = .063$ . To control the order in which participants performed the verbal and spatial single-task and dual-task conditions, we included task order as an independent variable in the statistical analyses. A Task Condition (single task vs. dual task)  $\times$  WM Domain (verbal vs. spatial)  $\times$  Task Difficulty (easy vs. difficult)  $\times$  Task Order (single task first vs. dual task first) ANOVA with repeated measures on the first three factors was performed on memory performance. This ANOVA obtained a significant interaction between task condition, WM domain, and task difficulty,  $F(1, 21) = 20.997$ ,  $p < .001$ ,  $\eta_p^2 = .500$ . The other three interactions also yielded statistical significance: task condition and WM domain,  $F(1, 21) = 80.670$ ,  $p < .001$ ,  $\eta_p^2 = .793$ ; task condition and task difficulty,  $F(1, 21) = 9.568$ ,  $p = .006$ ,  $\eta_p^2 = .313$ ; WM domain and task difficulty,  $F(1, 21) = 170.222$ ,  $p < .001$ ,  $\eta_p^2 = .890$ . Moreover, there were significant main effects of task condition,  $F(1, 21) = 99.877$ ,  $p < .001$ ,  $\eta_p^2 = .826$ ; WM domain,  $F(1, 21) = 32.977$ ,  $p < .001$ ,  $\eta_p^2 = .611$ ; and task difficulty,  $F(1, 21) = 278.997$ ,  $p < .001$ ,  $\eta_p^2 = .930$ . However, task order had no statistical influence on memory performance ( $F$ s  $< 1$ ).

That is, as a consequence of the placing movement in the dual task, mean memory performance decreased compared with that in the single-task condition in the spatial (2.83 items,  $SD$  = 0.80),  $t(24) = 10.121$ ,  $p < .001$ , but not in the verbal WM task (4.14

items,  $SD = 0.45$ ),  $t(24) = 0.278$ ,  $p = .783$ . Importantly, there was a decline on both spatial tasks, the easy version (3.18 items,  $SD = 0.88$ ),  $t(24) = 9.221$ ,  $p < .001$ , and the difficult version (2.47 items,  $SD = 0.76$ ),  $t(24) = 7.156$ ,  $p < .001$ , but on none of the verbal tasks, neither the easy version (4.27 items,  $SD = 0.48$ ),  $t(24) = 0.659$ ,  $p = .516$ , nor the difficult version (4.01 items,  $SD = 0.46$ ),  $t(24) = 1.975$ ,  $p = .060$  (see Figure 3). Hence, the data of Experiment 2 support the assumption that movement execution has a domain-specific influence on visuospatial information in WM. There was a performance drop induced by the secondary motor task (dual task) compared with single-task performance in both versions of the spatial task but not in the verbal tasks.

## Discussion

Experiment 2 tested whether the domain-specific influence of motor activity on spatial WM performance that we found in Experiment 1 was actually caused by differences in task difficulty between the verbal and the spatial WM task. We addressed this question by comparing single-task performance (no movement) with dual-task performance (manual placing movement) in easy and difficult versions of a verbal and a spatial WM task. The results of Experiment 2 confirm the results of Experiment 1 by showing performance dissociations between verbal and spatial WM capacities induced by the concurrent placing movement. There was a performance decline in both the easy and difficult versions of the spatial WM task, but in none of the verbal WM tasks.<sup>1</sup> That is, the execution of the prepared placing movement selectively interfered with the short-term maintenance of spatial information. As the planning of the forthcoming movement was completed before the information was encoded into WM, it was the execution of the movement that either required cognitive capacities involved in the rehearsal of spatial information in WM or disrupted the mechanisms involved in memory rehearsal. The interference between movement execution and spatial WM was domain-specific and independent of the processing demands of the WM tasks. Consequently, the results of Experiment 2 are in line

with the results of Experiment 1 and support the assumption of domain-specific execution costs on memory.

The next experiment concerned the question of whether processes involved in replanning discrete goal-directed movements interact differently with information held in WM than those processes involved during the execution of these movements. That is, Experiment 3 was designed to address the question of whether movement planning costs are separable from execution costs in the verbal and spatial WM domains.

## Experiment 3

Experiment 3 investigated the effects of movement planning processes during memory retention on verbal and spatial WM performance. More specifically, we tested whether movement execution costs and replanning costs produce distinct interaction patterns with verbal and spatial information. To approach this research question, we used the same dual-task scenario as described in Experiment 1. Again, participants planned to move the sphere toward one of the target positions (left vs. right), and subsequently encoded and maintained information in WM (verbal vs. spatial). In contrast to Experiments 1 and 2, the planned movement direction was either confirmed or reversed by one of two auditory cues before the participant executed the placing movement and reported the memory information. According to Quinn and Sherwood (1983), reversing the movement direction requires the implementation of a new motor program, whereas, for example, increasing the speed of an ongoing movement requires modification of a parameter variable. Hence, in addition to WM domain (verbal vs. spatial), this manipulation resulted in a movement planning (prepared vs. replanned) factor. In the prepared movement condition, participants executed the movement as planned. In contrast, in the replanning condition, participants had to replan their movement to the other target position after memory encoding.

Based on the results reported by Spiegel et al. (2012), we hypothesized that movement replanning would require cognitive resources that interact with information in WM. Therefore, we predicted a main effect of movement planning, with better memory performance after prepared compared with replanned movements. In addition, in accordance with the results of Experiments 1 and 2, we expected that movement replanning would affect spatial processes to a greater degree than verbal processes, resulting in an interaction between movement planning and the type of information held in WM. Therefore, we predicted an interaction between movement planning and WM domain on memory performance. Alternatively, if action replanning engages processes distinct from those underlying action execution costs, one may expect a different pattern of results. If it were the case that planning costs are not domain-specific, that is, are independent from execution costs, we expected only main effects but no interaction between movement planning and WM domain on memory performance.

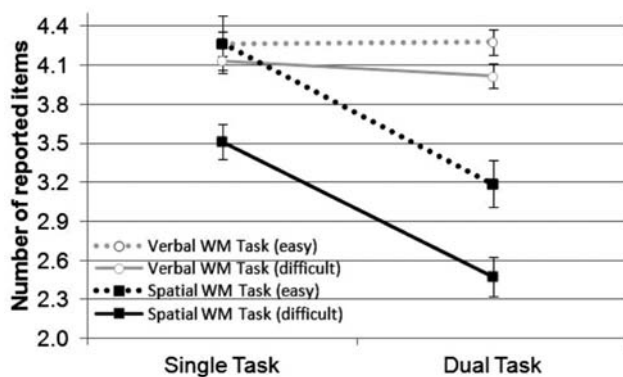


Figure 3. Mean memory performance in the easy and difficult versions of the verbal and spatial working memory (WM) tasks for the condition without movement (single task) and for the condition with a prepared placing movement (dual task) from Experiment 2, with error bars representing standard errors of the mean.

<sup>1</sup> The memory performance in the easy verbal WM task is unlikely to reflect a ceiling effect because the performance in the difficult verbal condition decreased numerically even though more items were presented for memorization.

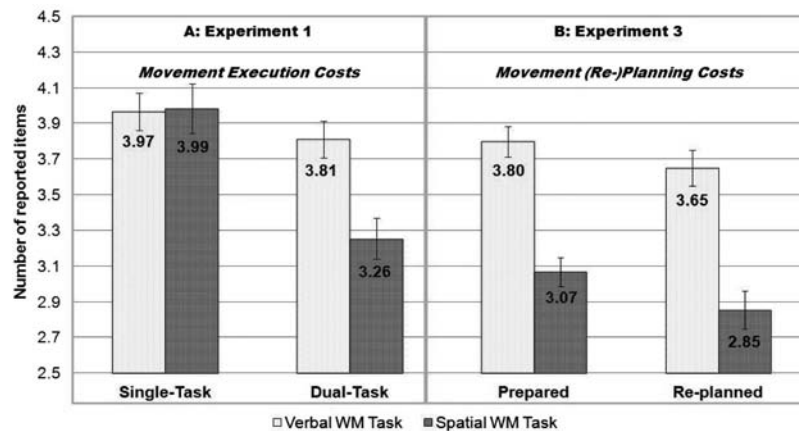


Figure 4. Memory performance in the verbal and spatial working memory (WM) tasks of Experiments 1 and 3, with standard error bars. (A) Movement execution costs as the performance decline in the dual-task condition (with secondary motor task) as compared with the single-task condition (memory task alone). (B) Movement (re-)planning costs as the performance decline in the replanned condition (implementation of new action plan required) as compared with the prepared condition (keep the prepared action plan).

## Method

**Participants.** Twenty-four right-handed students (12 women, 12 men,  $M$  age = 26.0 years,  $SD$  = 4.3, range = 21–36 years) with normal or corrected-to-normal vision were recruited to take part in this experiment. All participants were naïve to the hypotheses and gave informed consent prior to testing. Participation was compensated with either 5€ or 1 hr of participation credits. None of the participants in this experiment had participated in Experiment 1 or 2.

**Materials and procedure.** The apparatus and cue stimuli were identical to those used in Experiments 1 and 2. Again, both WM tasks were consecutively combined with the motor task to fit the sphere onto a target stick. Thus, the only difference between Experiments 3 and 1 was the requirement to replan the intended placing movement according to one of the two auditory cues, which participants were instructed to ignore in Experiments 1 and 2 (cf. Figure 1). Participants lifted the sphere from the starting position, moved it above the center of the setup, and planned the placing movement according to the preparation cue (arrow left or right). Importantly, after encoding the memory stimulus (verbal or spatial), participants heard one of the two auditory cues that either confirmed or reversed the planned movement direction. Instructions regarding the memory tasks and the motor task were commensurate with those of Experiments 1 and 2. Again, participants completed 10 practice trials prior to the experimental trials. The entire experiment lasted approximately 60 min.

Experiment 3 rested on a  $2 \times 2$  within-subjects design, with movement planning (prepared vs. replanned) and WM domain (verbal vs. spatial) as factors. The 100 verbal and 100 spatial experimental trials were presented in blocks of 50 trials, with self-paced breaks after each block. In each WM domain, 80 trials did not require changing the current action plan (80%), whereas 20 trials required implementation of a new action plan (20%). We decided to choose an 80/20 ratio for the prepared and the replanned trials as this procedure has commonly been used in studies of the kinematics of adaptive movements (Castiello et al., 1993, 1998;

Paulignan, Jeannerod, et al., 1991; Paulignan, MacKenzie, et al., 1991) as well as in those that tested the impact of infrequent events on a dependent variable (e.g., Posner, 1980). Moreover, by video recording the participants' grasp-to-place movements, Spiegel et al. (2012) demonstrated that participants planned the forthcoming movement according to the directional arrow when 80% of the trials were valid and 20% invalid (replanning was required).

The order of presentation of the WM domain was counterbalanced, that is, half of the subjects started with the verbal trials and the other half started with the spatial trials. Stimuli were randomly presented, and the assignment of replan and stay auditory cues was counterbalanced between participants.

## Results

Mean memory performance was 3.77 letters ( $SD$  = 0.43) in the verbal task and 3.02 symbols ( $SD$  = 0.40) in the spatial task. A three-way ANOVA with the factors WM Domain (verbal vs. spatial)  $\times$  Movement Planning (prepared vs. replanned)  $\times$  Task Order (verbal first vs. spatial first) with repeated measures on WM domain and movement planning revealed both a main effect of WM domain,  $F(1, 22) = 36.178$ ,  $p < .001$ ,  $\eta_p^2 = .622$ , and a main effect of movement planning,  $F(1, 22) = 14.204$ ,  $p = .001$ ,  $\eta_p^2 = .392$ . However, there were no interactions between the factors, nor did task order affect memory performance ( $F < 1$ ). That is, as a consequence of replanning, memory performance decreased in both the verbal and spatial WM tasks. This performance drop was similar in both WM tasks. Nevertheless, further analyses revealed that subjects performed significantly better overall in the verbal compared with the spatial WM task in both the prepared,  $t(23) = 6.158$ ,  $p < .001$ , and the replanned conditions,  $t(23) = 5.466$ ,  $p < .001$ .

Additional between-experiments analyses revealed that subjects in the prepared condition in Experiment 3 performed equally as well as participants in the dual-task condition in Experiment 1; this was true in both the verbal,  $t(46) = 1.47$ ,  $p = .908$ , and the spatial WM task,  $t(46) = 3.47$ ,  $p = .163$  (see Figure 4). This result is not



surprising as the only difference between the prepared condition in Experiment 3 and the dual-task condition in Experiment 1 was the subjective uncertainty of a possible replanning requirement. The relative performance difference observed in the dual-task condition in Experiment 1 between the verbal and the spatial WM tasks (relative concurrence costs), with overall better performance in the verbal task, was retained in both the prepared and replanned conditions in Experiment 3. In other words, based on the relative performance difference between verbal and spatial WM tasks in the dual task, the additional planning requirement reduced performance in both WM tasks to the same degree. Importantly, the relative movement execution costs were not due to the spatial WM task being more demanding than the verbal WM task per se, as was shown in Experiment 2 and evidenced by equal performance in both WM tasks in the single-task conditions in Experiment 1 and 2.

## Discussion

The results of Experiment 3 show that replanning a placing movement reduced performance in both the verbal and spatial WM tasks. By comparing performance in a prepared condition (keep the prepared action plan) with performance in a replanned condition (implementation of new action plan required) in verbal and spatial WM tasks, we provide a method to measure movement planning costs in the verbal and spatial domains. We found similar planning-related performance costs in both WM tasks.

Therefore, on the one hand, this result confirms our prediction of motor replanning reducing memory performance and is in line with the results recently reported by Spiegel et al. (2012). On the other hand, we demonstrate that the additional movement planning interfered equally with both types of information that were temporarily stored in WM, suggesting that the engagement of WM resources for action replanning is non-domain-specific.

## General Discussion

The main purpose of this study was to clarify what kind of WM processes (verbal, spatial, or both) are recruited during movement planning and movement execution. Therefore, we combined verbal and spatial WM tasks with a high-precision manual action and tested the impact of simultaneous movement execution on memory retention (Experiment 1), the role of WM task difficulty as a moderating variable in motor-memory interactions (Experiment 2), and the impact of implementing a new motor plan during memory retention (Experiment 3).

Our data show that movement planning and movement execution recruit distinct WM capacities. In the first experiment, we demonstrated that movement execution had a domain-specific impact on spatial WM performance, a finding we replicated in Experiment 2 for WM tasks of varying difficulty. In Experiment 3, in contrast, movement planning that was required during memory retention after the movement had already been initiated decreased memory performance over and above the execution costs. These planning-associated costs were non-domain-specific as they reduced performance in both the verbal and spatial tasks to a similar degree.

Movement planning and movement control are commonly regarded as two functionally distinct components of goal-directed

actions (Elliott et al., 2001; Jeannerod, 1984b; Woodworth, 1899; for a review, see Glover, 2004). Support for a fractionation of movements into functional components comes from neuroimaging studies, which have provided evidence for distinct brain networks involved in the planning and control of even simple reaching and grasping actions (e.g., Fridman et al., 2006; Glover et al., 2012; Johnson-Frey, Newman-Norlund, & Grafton, 2005; Krams, Rushworth, Deiber, Frackowiak, & Passingham, 1998). However, as interference with WM processes has been shown for both movement planning (e.g., Spiegel et al., 2012) and movement control (e.g., Logan & Fischman, 2011), it has remained unclear to what extent the two movement phases contribute sources of interference with information in WM. The present research provides comparative analyses of planning- and execution-related costs in verbal and spatial WM.

Within the multicomponent model of WM (Baddeley, 1986), the finding of different interference patterns in WM can be interpreted as the two movement phases drawing on distinct specialized WM components. Importantly, the domain-specific performance decrease in the spatial task was not due to the spatial WM task being more difficult per se, as was shown in Experiment 2. In the second experiment, the domain-specific interference between movement execution and the maintenance of spatial information was retained in the easy and difficult versions of the spatial task but in none of the verbal tasks. Hence, the execution and control of the action occupied domain-specific WM capacities. This result is consistent with Baddeley's (1986) hypothesis of separate verbal and visuospatial subsystems in WM. Within this model, the verbal and spatial versions of the WM task can be interpreted as each drawing on separate specialized resources. Whereas storing and rehearsing the letters was mainly accomplished by the phonological loop, the visuospatial sketchpad was responsible for storing and rehearsing information about the symbols' positions. The execution of the prepared placing movement during memory retention impaired performance predominantly in the spatial task, suggesting that the impaired recall is caused by interference between movement control and cognitive capacities involved in the visuospatial sketchpad.

Possible mechanisms for this selective interference relate to execution-related interruption of the rehearsal processes in spatial WM. Importantly, the inner scribe, the component responsible for dynamic retrieval and rehearsal within the sketchpad (cf. Logie, 1995), may be involved in the extraction of information used in the execution of voluntary movements and is further assumed to bind visual information with motor, tactile, or haptic information (Baddeley, 2001). Hence, rehearsing information of the spatial WM task and executing the placing movement at the same time might have caused interference within the inner scribe component. Alternatively, fitting the sphere onto the stick required a certain amount of precision, which in turn required spatial attention and oculomotor control, both assumed to be involved in maintaining information in spatial WM (e.g., Awh et al., 1998, 1999; Lawrence et al., 2001). Hence, control of the manual action might have interfered either by interrupting memory rehearsal or by recruiting attentional and/or oculomotor control resources that were also required for memorization (cf. Theeuwes, Belopolsky, & Olivers, 2009).

It has been discussed whether interference with the maintenance of spatial information in WM is caused by movement activity itself

or rather by the shifts of attention that naturally accompany a movement (e.g., Boulinguez & Nougier, 1999; Shepherd, Findlay, & Hockey, 1986). To approach this question, Lawrence et al. (2004) dissociated movement-related and attention-related effects on the maintenance of spatial information in WM by comparing memory performance in conditions in which a secondary task required fixation, an eye movement, or an attention shift executed in the absence of an eye movement. Their results revealed greater movement-related than attention-related effects on spatial WM. Lawrence et al. suggest that eye movements, or even all spatially directed movements (Lawrence et al., 2001), may contribute a unique source of interference with spatial working memory.

Moreover, the domain-specific interference pattern of the present Experiments 1 and 2 is concordant with those results reported from the Corsi block-tapping task (cf. Corsi, 1972; Milner, 1971; Vandierendonck, Kemps, Fastame, & Szmalec, 2004), which has been used as a measure of spatial memory span in adults (e.g., Orsini et al., 1986; Smyth & Scholey, 1992), children (e.g., Farrell Pagulayan, Busch, Medina, Bartok, & Krikorian, 2006; Purser et al., 2012), and in clinical contexts (e.g., D'Agati, Cerminara, Casarelli, Pitzianti, & Curatolo, 2012; Gould & Glencross, 1990; Rotzer et al., 2009; Vilkkii & Holst, 1989). In the Corsi block-tapping task, participants are required to observe and repeat a sequence of blocks "tapped" (or lit up, in the computer version). As the length of the sequences gradually increases, the spatial WM span is defined as the longest correct sequence remembered. Similar to the high-precision manual action used here, the execution of the spatial tapping task seems to call on the visuospatial sketchpad rather than the phonological loop.

We interpret the domain-specific execution costs as interferences within the specialized short-term store for visuospatial information (the sketchpad), whereas the planning-associated costs, in contrast, can be interpreted as drawing on the central executive, the attentional control system in WM (Baddeley, 1986, 1992, 1996b). The idea of the central executive component developed from the supervisory attentional subsystem (SAS) model of Norman and Shallice (1986), which was the only model that attempted to explain the attentional control of action at that time (cf. Baddeley, 2001). Like the SAS, the central executive is of limited attentional capacity and is capable of combining information from different sources to plan novel solutions and to ensure that an action plan is followed. This component is typically assumed to be responsible for controlling attention, coordinating the two proposed WM slave systems, and dividing or switching attention between tasks, when necessary (Baddeley, 1996a; Baddeley, Chincotta, & Adlam, 2001; Della Sala, Baddeley, Papagno, & Spinnler, 1995). Support for the existence of the central executive comes from studies with healthy participants (e.g., D'Esposito et al., 1995) and from studies with patients with defined frontal lobe lesions who show selectively impaired capacity for dual-task coordination (Baddeley, Della Sala, Papagno, & Spinnler, 1997; Roussel, Dujardin, Henon, & Godefroy, 2012; also see Andres, 2003). So far, it remains unclear whether the central executive comprises a single unitary controller or whether it can be fractionated into separable executive processes (cf. Baddeley, 2010; Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999; Shallice & Burgess, 1996), such as a specific switching system that allows disengaging and reengaging the attentional focus (Baddeley, 1996a; Posner & Petersen, 1990).

Attentional control is necessary in unfamiliar situations or when unexpected changes occur, such as the requirement to change movement direction in Experiment 3. Reversing movement direction, which required the implementation of a new motor program (Quinn & Sherwood, 1983), seemed to increase the general dual-task demands of Experiment 3 as compared with Experiment 1, which was identical to Experiment 3 except for the infrequent replanning requirements. The cognitive operations involved in movement replanning can be interpreted as engaging attentional capacities involved in the central executive. Interpreting the new plan from instructions and implementing the new action plan seemed to recruit general attentional resources in the central executive. The equal performance decline in both domain-specific WM tasks might reflect the common central executive contribution to the two slave systems of WM (Baddeley, 1996a). We interpret the additional planning costs as being a load on general central executive resources that came on top of the domain-specific execution costs as participants had to execute the movement after replanning it.

With respect to alternative WM models that suppose that attention itself serves as the holding device and is the limiting factor for storage capacity (Cowan, 2001), one might argue that implementing a new action plan requires additional resources that are drawn away from both WM tasks. To fit the sphere onto the correct target in the replanning trials, participants had to interpret from instructions the meaning of the infrequent tone, access the active target representation (pointing direction of the arrow), inhibit the previous action plan, and implement a new action plan to reverse the movement direction. More precisely, participants had to remap the active stimulus-action binding by selecting a different response (a placing movement to the opposite direction) to the stimulus (the directional arrow; cf. Oberauer, 2009). This cognitive operation might have required additional attentional capacities, resulting in fewer resources available for the maintenance of both verbal and spatial information in WM. On the basis of the present data, we cannot examine the exact role of attention in the context of movement planning and control. However, we suggest that attentional control plays an important role, especially in the implementation of action plans. Limited attentional capacities seem to be functionally involved in explaining the sources of interference between movement and WM processes.

It is important to note that the influence of action on memory performance is not only disruptive in nature, but can also facilitate memory performance. For example, Chum, Bekkering, Dodd, and Pratt (2007) demonstrated enhanced recognition performance for spatial arrays that were encoded with both a perceptual and a motor code (pointing to each presented spatial item) compared with arrays that were encoded via a perceptual code only (passively observing each item). The authors suggest that actively pointing to to-be-memorized items leads to action-based encoding in WM in terms of increased spatial-based perceptual bias and increased egocentric coding. However, Dodd and Shumberski (2009) demonstrated that simply adding a motor trace to the perceptual trace during memory encoding does not necessarily enhance memory performance but, in contrast, is more likely to reduce memory performance because of the additional resources required to engage motor activity. According to Dodd and Shumberski, a facilitative effect can be found when a subset of items is explicitly selected (by pointing to it) for additional processing, that

is, selected for action, as compared with the nonselected items for which processing in turn is reduced.

Hence, interactions between memory and action processes seem to be complex and dependent on a variety of factors, such as, as demonstrated here, the type of temporarily stored information (verbal vs. spatial) and which movement phase (planning vs. control) is currently processed. Moreover, other factors, such as the mode of memory selection (Dodd & Shumborski, 2009), the precision requirements of the motor task (Spiegel et al., 2012), and whether the action decisions were freely chosen or instructed (Fleming, Mars, Gladwin, & Haggard, 2009), may also moderate interactions between motor and memory tasks. In investigating the neural correlates underlying the processes of changing one selected action plan for another, Fleming et al. (2009) found differences between the neural responses related to the updating of free compared with instructed actions. Free action choices were associated with lower P300 amplitudes in response to change cues than instructed action. Relating the P300 to "context updating" (Donchin & Coles, 1988), Fleming et al. interpret the P300 differences as freely chosen actions being more flexible and modifiable than instructed plans. Accordingly, future studies should further investigate the mechanisms involved in moderating the movement-related costs we have reported here. For example, one might expect differential replanning costs depending on whether the action intention was freely chosen or experimentally instructed. Furthermore, varying the response mode (vocal vs. manual) for the WM stimulus (verbal vs. spatial) is an important manipulation to carry out in future investigations as it is conceivable that the specific pairing of stimulus and response modality is a potentially relevant factor in this experimental design (cf. Hazeltine & Wifall, 2011; Stelzel & Schubert, 2011). Nevertheless, results of the present study suggest that, whatever mechanisms involved, executing goal-directed movements interfered with spatial WM primarily by disrupting processes localized in the visuospatial sketchpad, whereas implementing a new action plan recruited non-domain-specific central executive capacities.

In summary, the results of the present study show that movement (re-)planning costs and movement execution costs are separable in verbal and spatial WM. Our data suggest that both movement phases recruit distinct WM capacities and may therefore constitute a unique source of interference. More specifically, the physical activity of the goal-directed placing movement interfered more with the short-term storage of spatial information than with the storage of verbal information. We replicated this specific interference pattern for easy and difficult versions of verbal and spatial WM tasks. These results of Experiments 1 and 2 suggest that movement execution costs in WM are domain-specific. In Experiment 3, in contrast, the costs of replacing one action plan with another action plan were greater than the execution costs and appeared to be non-domain-specific. Performance on the verbal and spatial versions of the WM task was likewise reduced by the action replanning beyond the relative concurrence costs observed in Experiment 1. Together, the results of the present study suggest that the WM engagement involved in movement replanning (movement planning costs) is functionally distinct from that involved in performing a prepared movement (movement execution costs). Using verbal and spatial WM measures to investigate the costs of action (re-)planning and action execution provides new insights into the cognitive organization of action.

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