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Individual differences in interrupted task performance: One size does not fit all ☆

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ABSTRACT

Two experiments used a spatial navigation task to study the relationship between individual differences in working memory capacity and interrupted task performance. The results of experiment one show that participants with low working memory capacity (WMC) are more susceptible to the negative effects of interruptions than participants with high WMC. The results of additional analyses indicate that both groups differ in their strategies used to memorize material from the primary task. A second experiment manipulated memory strategy use for high and low memory span participants and found that low span participants performed at the level of high spans when using a strategy that is more typically used by high span participants. However, this performance improvement did not show during interrupted tasks. Overall, these results suggest that individual memory capacity differences affect performance during interrupted tasks by determining selection of memory strategies and by limiting performance of participants.

Working memory (WM) is crucial for performing cognitive tasks (Unsworth and Engle, 2007), and is highly correlated with general fluid intelligence (Engle et al., 1999; Jaeggi et al., 2008; Kane and Engle, 2002) and executive attention (Engle, 2002). Engle et al. (1999) define working memory capacity (WMC) as the ability to temporarily maintain representations activated in the face of distraction, e.g., interruptions. Sweller (1988) refers to information that is processed in working memory as cognitive load with increases in cognitive load utilizing a person's finite working memory capacity.

Interruptions increase cognitive load, often by requiring processing of information that is not relevant to the primary task. For example, when facing an interruption (e.g., a notification of required operating system restart) a person may suspend a primary task (e.g., creating a table in a document) in order to address the interruption. During that time, information relevant to the primary task needs to be kept active in WM in order to allow resumption of the primary task (Trafton et al., 2003). Information maintained may include steps of the primary task already performed (e.g., determining the number of columns and rows of the table, insertion of the table, entering some of the headers into the table), the step that was active at the time of interruption (e.g., formatting of the table), and how one had prospectively planned to proceed (e.g., adding borders to the table) (Boehm-Davis and Remington, 2009). Further, a person may have to store information about the interrupting task in WM until task completion (e.g., performing manual system restart). Failure of working or prospective memory will result in execution errors upon return to the primary task. Recent cognitive models of interruptions, e.g., Altmann and Trafton's (2002) memory for goals model, specify these cognitive processes involved in WM.

Another aspect of WM is that it is associated with controlled, but not automatic processing. Unsworth and Engle (2005) demonstrated significant differences between participants with high and low WM span scores in task performance of a difficult task that requires controlled processing. The authors found no differences between groups in automated tasks. However, interrupted task performance entails controlled processing because the disruption requires operators to decide whether to proceed with the interrupting task, rehearse completed steps, and prospectively encode goals. Thus, a difficult primary task, which requires controlled processing is more demanding and requires more cognitive control with the onset of an interruption. Consequently, interruptions will exacerbate any impact on primary task performance across different abilities of WM, and this impact likely increases with greater task difficulty.

A review of the interruption literature indicates that previous research predominantly investigated task and interruption characteristics, for example, timing (Adamczyk and Bailey, 2004), duration (Altmann and Trafton, 2002; Gillie and Broadbent, 1989), or complexity (Cades et al., 2008; Monk et al., 2008) of interruptions, or complexity of the primary task (Speier et al., 2003). Overall, research focused primarily on characteristics external to the person rather than

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on theoretical underpinnings of interruptions involving human cognitive processes (Biron et al., 2009). Thus, one of the limitations of this body of work is that it does not identify how interruptions differentially affect performance of individuals in their abilities to plan, recall, and execute tasks (although see Brumby et al., 2013). The goal of this work is to advance the research on interruptions by adding a complementary perspective to this research: How do characteristics of the individual affect performance during interruptions. An improved understanding of this impact would allow for more effective human computer interaction because by anticipating the user specific impact of interruptions, it would be possible to manage interruptions in such way that they have the least impact. For example, for some users interruptions could be completely blocked while interacting with the computer, for others only selected interruptions would be active, while for another group, no suppression of interruptions would occur.

Engle (2002) explains that individual differences in WMC are an important predictor for performance on higher-order cognitive tasks (e.g., problem solving, decision making and reasoning) (Just and Carpenter, 1992). Higher WMC is associated with better goal maintenance and increases resistance to the negative effects of interference. Kane and Engle (2000) note that people with low WMC are more susceptible to proactive interference under dual-task conditions compared to single task conditions. Other research demonstrated similar effects of retroactive interference on working memory (Hedden and Park, 2003). Based on these findings, it is likely that interruptions affect people with higher WMC less than those with lower WMC.

In addition, different cognitive abilities may also lead to differences in how a person plans how to deal with an interruption. Thus, higher WMC may lead to use of a more cognitively demanding strategy that increases WM requirements, whereas lower WMC may lead to the use of less cognitively demanding strategies.

1. Interruptions and error

One way that interruptions can cause errors is by increasing the cognitive demand on an individual. Capacity interference (Kahneman, 1973) occurs when there is too much information present for an individual to successfully process. During difficult tasks, a person's mental workload may be at or near capacity limits (Evaristo et al., 1995). In such a situation, the additional cognitive demands imposed by an interruption can overload the individual's processing limits (Speier et al., 1999) which decreases performance and increases error.

While performing a primary task (PT), a person often plans a sequence of steps necessary to accomplish that task (e.g., the steps required to create a table in a document). This can be cognitively demanding, especially if the PT requires accurate and efficient execution. In environments where interruptions are prevalent, a person's ability to plan effectively may be impaired even by the anticipation of an interruption (Loft et al., 2008). In these situations, a person must not only encode goals and steps, but also prepare for the possibility of interruption. Anticipation of an interruption can impede performance more than being surprised by an interruption (Loft et al., 2008). These findings suggest that preparation for an interruption requires additional cognitive resources. One potential outcome of a failure to mobilize additional resources during an interruption are post completion errors (Li et al., 2008), where the temporal proximity of an interruption to a post completion step increases the likelihood of error.

Above, it was argued that interruptions impair performance and contribute to error. Here we distinguish between two types of error: Planning errors and execution errors (Altmann, 2004; Altmann and Trafton, 2002). Planning errors occur during the encoding of necessary task steps in prospective memory. They manifest themselves in incorrect or sub-optimal intentions. Execution errors occur during the recall of previously encoded goals and steps. Execution errors may involve optimal planning, but memory failure results in incorrect recall of that plan. Planning errors and execution errors map into the distinction between mistake and slips (for more detail see Norman, 1983).

The present work investigates the question how individual differences in WMC affect task performance and error rates in interrupted tasks. We present the results of two studies with the first examining the impact of WMC on a person's ability to deal with interruptions, and the second exploring how strategy use affects performance in interrupted tasks.

2. Experiment 1

The goal of the first experiment is to investigate the contribution of WMC on interrupted task performance and error rates across varying WM spans. The prediction is that high spans have lower execution error rates during interrupted PT trials than low spans. In addition, we expect an interaction between WM span and difficulty of PT such that low spans will show greater increases in error rates due to interruptions over increasing difficulties of PT compared to high WM span participants. Finally, planning ability will be affected during trials following an interruption with high WM span participants having lower planning error rates. Similar to predictions for execution error rates, an interaction between WMC and primary task difficulty is expected, such that low span participants will have higher planning error rates over increasing difficulty of PT compared to high span participants.

2.1. Methods

2.1.1. Participants

104 participants (57 females and 47 males) ranging in age from 18 to 27 ($SD=2.48$) took part in the study. Absolute Aospan scores were used to group participants into four groups of WMC with participants with scores in the lowest quartile (scores less than or equal to 25) being categorized as low spans, and participants with scores in the highest quartile (scores greater than or equal to 53) being categorized as high spans. Participants outside these two categories were excluded from further analyses, leaving 51 participants (29 females and 22 males) ranging in age from 18 to 27 ($M=20.8$, $SD=2.48$). The mean absolute Aospan score for the high span group was 58.64 ($n=26$; $SD=3.98$) and the low span group had a mean score of 15.23 ($n=25$; $SD=5.51$).

All participants were undergraduate students at the University of Utah and randomly assigned to one of three PT difficulty conditions.

2.1.2. Materials

2.1.2.1. Spatial navigation task. For the purpose of this study we developed a task that included features that are common in many everyday tasks. The primary task (PT) involved spatial planning navigation, which required participants to plan, recall, and execute spatial movements in order to move a cursor to a specific goal (see Fig. 1a).

The navigation space contained the starting and goal position, movement obstacles and movement facilitators. A navigation problem was comprised of the successful movement of the cursor from the starting point to the goal using the smallest number of instructions possible. A problem consisted of six trials with each trial being divided into three phases (Fig. 2a).

During the *planning* phase participants saw the movement space (Fig. 1a) and the movement instructions (e.g., “Turn left”, “Forward 2”, “Turn right”, “Forward 3”, “Back up 1”, “Do nothing”, “Forward 1” and

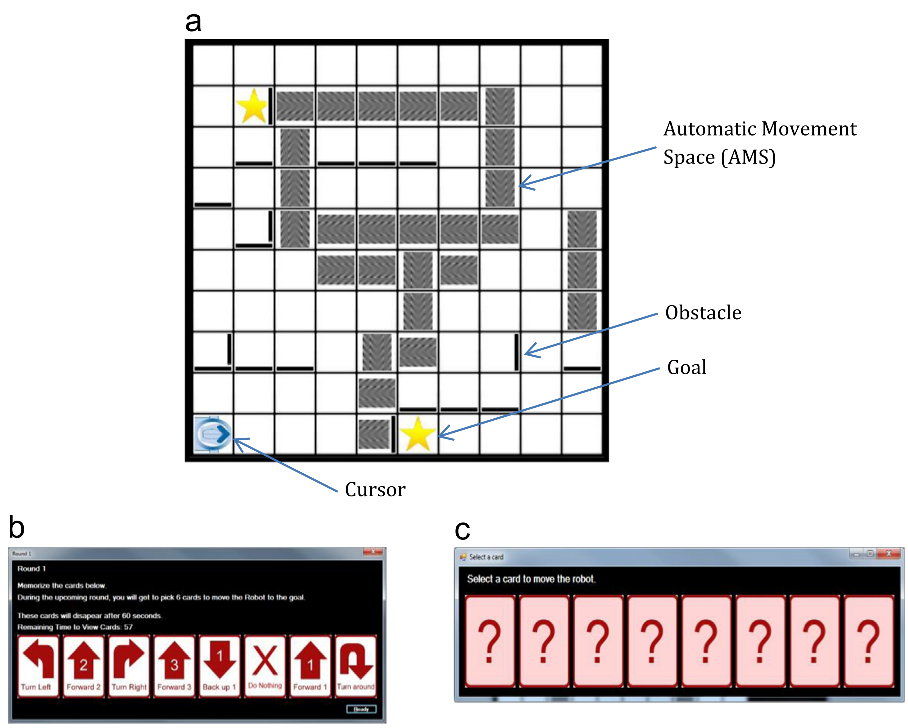

Fig. 1. Screenshots of the spatial navigation task. The 10 × 10 grid of squares (a) comprises the movement space. During the planning phase (b) participants study instructions that they can select to navigate the cursor. Instructions are obscured (c) during the execution phase.

"Turn around", Fig. 1b) on the screen, identified which instructions to select to move the cursor (e.g., turn left, do nothing), and determined the instruction execution order (Fig. 1b). The order of instruction presentation was randomized for every trial. During the *prediction* phase, participants predicted the intended cursor position by marking this position by mouse click on the screen that displayed the movement space (Fig. 1a). During this phase only the movement space was presented. At the beginning of the *execution* phase participants saw obscured movement instructions, each in identical position as during the planning phase (see Fig. 1c). With the instructions being obscured participants had to rely on the previously encoded plan to select the memorized movement instructions. Immediately after selection of an individual instruction (e.g., second instruction on the left: forward 2) the instruction was executed on the movement space (Fig. 1a), moving the cursor two spaces forward. The completion of the execution of the last available instruction terminated the trial. Participants were allowed to use as much time as needed to complete the three phases, with the exception of the planning phase, where the display of the instructions was limited to 60 s.

To manipulate the PT difficulty, the movement instruction set size varied (i.e., in the easy condition, participants selected 5 out of 7 available instructions, in the moderate condition, they selected 6 out of 8 instructions, and in the difficult condition, participants selected 7 out of 9 instructions).

To avoid potential floor effects, the overall difficulty of the navigation task was increased by including automatic movement spaces (AMS). These AMS executed additional cursor movements in the indicated direction, providing opportunity for more efficient cursor movement.

While on the surface lacking a resemblance to many computer tasks performed daily, underlying the spatial navigation task are features that are typical for many everyday tasks. Among the shared features between everyday tasks (e.g., creating a table in a document) and the spatial navigation task are: (1) a defined beginning and end state, (2) a set of procedures to transform the beginning state into the end state, (3) a number of specific procedures available, (4) with some procedures being more efficient than others, and (5) constraints that require either additional planning or improvisation. Table 1 describes these features.

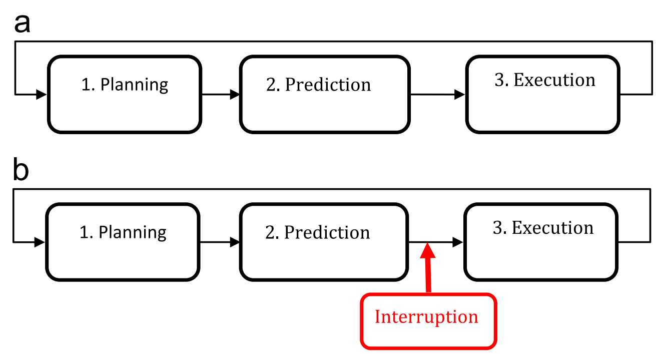

Fig. 2. Procedure for one trial of the navigation task. (A) The sequence of a non-interrupted trial, and (B) the sequence of an interrupted trial. Each trial consisted of three phases with participants required to study instructions and formulate a plan (1. Planning phase), predict the result of their plan (2. Prediction phase), execute their plan one instruction at a time (3. Execution phase).

Participants performed two navigation problems of which 66% of the trials were interrupted (after completion of the prediction phase; see Fig. 2B).

2.1.2.2. Interrupting task. The interrupting task consisted of either a short N-back task or a short Automated Operation Span (Aospan) task of 10 min duration. The N-back task (Gevins and Cutillo, 1993) requires from a participant to monitor a series of stimuli. Participants are instructed to respond to a stimulus whenever the stimulus presented is the identical to a stimulus presented *N* trials previously ($n=4$). The Aospan task is a variation of the operation span task (Unsworth et al., 2005) where participants determine whether mathematical equations are true or false. After each equation, the participant memorizes a letter shown on the display. Between three and seven equation/letter pairs constitute a block after which participants are required to recall the letters previously encoded in the correct order.

Table 1
Comparison of selected features between navigation task and task of creating a table.

Features	Navigation task (examples)	Task of creating a table in a document
Defined beginning and end state	Cursor at start position Cursor at end position	No table Table completed
Set of procedures	Turn right Forward 3	Shade elements Add borders Format borders
Efficient procedures	Automatic movement space	Standard table layout
Less efficient procedures	Individual movements	Layout completely customized
Constraints	Movement obstacles	Requirement to specify table size before formatting

2.1.3. Procedure

Each participant's session took approximately 90 min and included a WM assessment (Aospan), and the spatial navigation task.

2.1.4. Measures

2.1.4.1. Span group. Total scores for the Aospan task determined assignment of participants to memory span groups (see above).

2.1.4.2. Execution error rates. An execution error was operationalized as the difference between actual and predicted location of the cursor at the end of a trial. Execution error rates were the average of these deviations across trials.

2.1.4.3. Planning error rates. A planning error was identified based on a spatial difference between the predicted location of the cursor and its optimal location. The optimal location was determined for each trial by considering the initial location of the cursor and the instructions available. Planning error rates were calculated as the average of deviations across trials.

2.1.4.4. Number of instructions to destination. The number of instructions to destination was the sum of instructions selected before reaching the goal. This score was computed independent of trials to account for differences in number of instructions available across varying difficulty conditions: since participants in the difficult condition implemented two additional instructions per trial compared to the participants in the easy condition, those in the difficult condition could have navigated to the goal in fewer trials, but not fewer instructions.

2.1.4.5. AMS usage. AMS usage was measured to determine whether a participant chose to use the AMSs to increase efficiency.

2.2. Results

2.2.1. Execution errors

For interrupted trials, the average number of execution errors for low spans in the easy (M=1.7, SD=0.38), moderate (M=2.2, SD=0.32) and difficult conditions (M=2.8, SD=0.59) were, in general, larger than those for the high spans (easy: M=1.7, SD=0.35; moderate: M=1.8, SD=0.50; difficult: M=2.0, SD=0.75). Similarly, during non-interrupted trials (Fig. 3), the average number of low span execution errors (easy: M=0.8, SD=0.29; moderate: M=0.9, SD=0.28; difficult: M=1.1, SD=0.35) was larger than the number of high span execution errors (easy: M=0.7, SD=0.19; moderate: M=0.8, SD=0.33; difficult: M=0.9, SD=0.25). Execution error differences were analyzed using a 2 (span group: high, low) × 3 (PT difficulty: easy, moderate, difficult) × 2 (interruption: present or absent) mixed-model analysis of variance (ANOVA). The statistical analysis revealed significant main effects due to span group, $F(1,45)=8.117$, $p<.01$, $\eta_p^2=.153$, PT difficulty, $F(2,45)=9.593$, $p<.01$, $\eta_p^2=.299$, and interruption, $F(1,62)=314.942$, $p<.01$, $\eta_p^2=.875$. To address more specifically the impact of interruptions, the next analysis included only interrupted trials. A 2 (span group: high, low) × 3 (PT difficulty: easy, moderate, difficult) ANOVA revealed main effects of span group, $F(1,45)=7.404$, $p<.01$, $\eta_p^2=.141$, and PT difficulty, $F(2,45)=8.332$, $p<.01$, $\eta_p^2=.270$. A set of planned comparisons indicated a significant difference between span groups for the difficult condition, $F(1,45)=11.407$, $p<.01$, $\eta_p^2=.202$, but not the easy, $F(1,45)=0.002$, $p=.961$, or moderate, $F(1,45)=1.918$, $p=.173$ conditions.

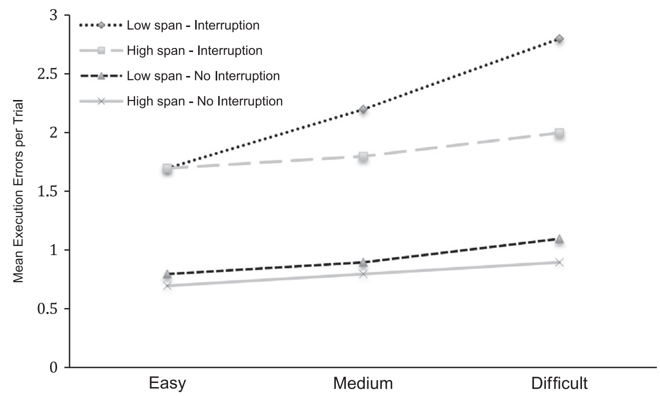

Fig. 3. Mean execution errors per trial across span group, interruption presence, and primary task difficulty.

2.2.2. Planning errors

Similar to execution errors, average numbers of planning errors per trial were analyzed using a 2 (span group: high, low) × 3 (PT difficulty: easy, moderate, difficult) × 2 (interruption presence: present or absent) mixed-model ANOVA. For trials that followed an interruption, the mean number of planning errors per trial for low spans in the easy (M=1.3, SD=0.36), moderate (M=2.1, SD=0.51), and difficult conditions (M=2.5, SD=0.69) was larger than for high spans (easy: M=1.1, SD=0.41; moderate: M=1.3, SD=0.42; difficult: M=1.4, SD=0.55 (see Fig. 4). Similarly, during trials that did not follow an interruption, low span average planning errors per trial (easy: M=0.56, SD=0.21; moderate: M=0.67, SD=0.18; difficult: M=0.93, SD=0.50) were larger than for high spans (easy: M=0.56, SD=0.26; moderate: M=0.59, SD=0.30; difficult: M=0.64, SD=0.33). The statistical analysis revealed significant within-subjects effects for interruption presence, $F(1,45)=176.385$, $p<.01$, $\eta_p^2=.797$. There were also significant between-subjects effects for span group, $F(1,45)=19.886$, $p<.01$, $\eta_p^2=.306$, PT difficulty, $F(2,45)=8.683$, $p<.01$, $\eta_p^2=.278$, and a span group × PT difficulty interaction, $F(2,45)=4.032$, $p=.03$, $\eta_p^2=.152$. Focusing the analysis on post-interruption trials only, the resulting 2 (span group: high, low) × 3 (PT difficulty: easy, moderate, difficult) ANOVA revealed main effects due to span group, $F(1,45)=24.737$, $p<.01$, $\eta_p^2=.355$, PT difficulty, $F(2,45)=8.658$, $p<.01$, $\eta_p^2=.278$, and an interaction, $F(1,45)=4.075$, $p=.02$,

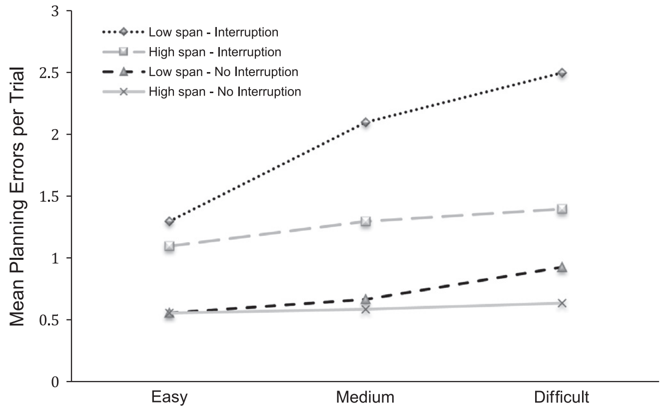

Fig. 4. Mean planning errors per trial across span group, interruption presence, and primary task difficulty.

η_p^2=.153. Planned comparisons indicated that the difference in planning errors between span groups was significant in the moderate, $F(1,45)=10.114$, $p<.01$, $\eta_p^2=.184$, and in difficult PT conditions, $F(1,45)=22.259$, $p<.01$, $\eta_p^2=.331$, but not the easy condition, $F(1,45)=0.513$, $p=.477$.

2.2.3. Time to complete PT

The independent samples t-test revealed a significant effect of span group $t(66)=2.115$, $p=.04$ on completion time, with low spans (M=65:25 min, SD=8:57 min) taking an average of 2 min and 1 s longer to complete the PT than high spans (M=63:24 min, SD=3:47 min).

2.2.4. Total number of instructions

For the first problem, participants required an average of 23 (SD=4.77) instructions, with optimal performance requiring 12 instructions. The fewest number of instructions used by participants was 15, and the largest was 37 instructions. High span participants required an average of 20.4 (SD=3.71) instructions, compared to 25.1 (SD=4.58) instructions used by low span participants. An ANOVA revealed a significant effect due to span, $F(1,45)=18.538$, $p<.01$, $\eta_p^2=.292$. All participants reached the goal in the first problem, while only 78% reached the goal in the second problem. Completion of the second navigation problem required an average of 42 (SD=7.08) instructions with optimal performance requiring 24 instructions. Again, high spans required fewer instructions (M=40, SD=6.85) than low spans (M=44.9, SD=6.58), $F(1,43)=5.740$, $p=.02$, $\eta_p^2=.118$.

2.2.5. Automatic movement space (AMS) usage

Another manifestation of efficiency in the PT was the use of automatic movement spaces (AMS). AMS usage indicated whether a participant used a cognitively more demanding, but efficient implementation of moves that required fewer instructions. Over the course of 12 trials, more high span participants (n=20, 80%) used AMS $\chi^2(1, n=51)=3.923$, $p=.05$, $\varphi=.277$, compared to 14 (54%) low span participants. Calculation of the odds ratio indicated that high spans were 3.43 times (95% CI: 1.0–11.9) more likely to use AMS than low spans. During interrupted trials, AMS use declined for both span groups (high: 56%; low: 19%) significantly $\chi^2(1, n=51)=7.371$, $p<.01$, $\varphi=.380$ with the odds ratio of AMS use favoring high span participants (odds=5.35; 95% CI: 1.52–18.75).

The number of instructions required to reach the first destination was negatively correlated with AMS use, $r(51)=-.337$, $p=.02$. Since higher AMS usage was associated with fewer instructions to reach the first destination, a further analysis aimed at understanding the interactions of these factors regarding interrupted task performance. A 2 (span group: high, low) × 3(PT difficulty: easy, moderate, difficult) ANCOVA, with AMS use as a covariate analyzed the number of instructions required to reach the goal. The results revealed a main effect due to span, $F(1,44)=13.585$, $p<.01$, $\eta_p^2=.236$, but not for PT difficulty, $F(2,44)=2.456$, $p=.10$ emphasizing the importance of memory span.

2.2.6. Additional Analyses

To control for performance differences between high and low span groups being a result of differential responses to the interrupting task, two additional analyses were performed. The results of the analyses that focused on both the number of execution errors, $t(49)=0.278$, $p=.78$, and the number of planning errors, $t(49)=0.291$, $p=.77$, indicated no difference based on interruption task type (brief Aospan vs. brief N-back).

2.3. Discussion

This first experiment examined if and how individual differences in WMC are associated with primary task performance during and after an interruption. Beyond the general finding that interruptions affect participants negatively, low span participants were affected more so across levels of difficulty of the PT. Next, the results will be discussed in more detail.

2.3.1. Execution errors

Overall, high span participants displayed fewer execution errors for interrupted and uninterrupted trials than low span participants. In addition, with increasing PT difficulty, execution error rates increased for both span groups. While this increase showed in all span group × interruption presence conditions, the impact was most pronounced for the low span participants during interrupted trials. This finding contrasts the uninterrupted PT trials, during which the trajectories for high and low spans were essentially the same. It is striking that the trajectory for high spans, when dealing with interruptions, has a similar shape, but at a higher level of execution errors compared to uninterrupted trials. Given the lack of a span group × PT difficulty interaction, the increase in observed execution errors is attributable to the presence of interruptions. Overall, low WM span participants display higher vulnerability to interruptions, which increases with PT difficulty.

2.3.2. Planning errors

Overall, the pattern of planning errors was remarkably similar to the trajectories observed for execution errors. However, the span group differences were more pronounced, with medium task difficulty separating both span groups in error numbers. In an applied context, this implies that frequently interrupted workers may anticipate interruptions, potentially affecting planning performance. Unfortunately, the impact is likely larger for individuals with lower WMC who are dealing with already cognitively demanding tasks.

2.3.3. Efficiency

High span participants were more efficient in accomplishing goals, e.g., high spans were faster, required fewer instructions, and used the AMS more effectively. Interestingly, during interrupted trials the odds for high spans using AMS stayed about the same compared to low spans, but the actual AMS usage declined for both groups. Thus, participants may have reverted to a less efficient and cognitively less effortful execution of instructions during interruptions. Additional support for this interpretation comes from findings reported by Wood et al. (1998) who show that participants revert to less effective methods in cognitively challenging situations.

Analysis of the number of instructions used to complete the first navigation problem indicated a significant effect due to span, but including AMS use during interrupted trials as a covariate,

Table 2
Strategy use by span group.

	Strategy	
Span group	Position N (%)	Complete N (%)
Low	19 (73.1%)	7 (26.9%)
High	6 (24.0%)	19 (76.0%)

eliminated this effect. Thus, AMS usage during interruptions accounts for the differences in number of instructions. This suggests that training low spans to use AMS, especially during interruptions, could increase their efficiency. In addition, individual differences played part in predicting who would choose a more efficient method of navigating the space, versus those who tended to choose a cognitively easier method of execution.

2.3.4. Strategies

That participants flexibly choose different methods in this study suggests that another factor may have also influenced participants' performance. It is possible that participants employed one of two strategies during the planning phase. One strategy, complete memorization (*Complete*), is to memorize the complete set of instructions (i.e., the serial position of an instruction and its associated movement information). This strategy provides flexibility during the execution phase, allowing participants to flexibly chose the instruction they want to use. However, use of this strategy imposes a high working memory load. The alternative requires less working memory, since it involves the memorization of the instruction position only. A participant using the position strategy (*Position*) memorizes only the positions of the instructions he or she intends to choose during the execution phase. A disadvantage is that after selecting an incorrect instruction a participant has no information about the specific movements associated with the instructions left. Thus, any further instruction selection is left to guess work and likely results in execution error. Post-hoc analyses of questionnaire data on of strategy use indicated that 76% ($n=19$) of the high spans adopted the *Complete* strategy (Table 2) whereas 73% ($n=19$) of the low spans used the *Position* strategy, a significant difference in strategy use, $\chi^2(1,\ n=51)=12.284$, $p<.01$, $\varphi=.491$ between the two groups.

Previous work of Daneman and Carpenter (1980) suggested that WM capacity is based on a person's use of strategy for a given task. For example, application of a more effective strategy for performance on a reading comprehension task includes chunking of information, which leads improved task performance (for similar work see also MacLeod et al., 1978; Reichle et al., 2000; Roberts et al., 1997). Engle et al. (1992) refer to this perspective as the task-specific view of WMC. In contrast Turner and Engle (1989) suggest that WMC is independent of specific tasks.

Empirical support for the first perspective is provided by Friederici et al. (1998) who identified memory strategy differences between high and low span participants during sentence processing tasks. The authors report use of a less effective strategy by low span participants, which is attributed to memory capacity limitations, whereas high spans use more elaborate and demanding strategies. Similarly, Kaakinen and Hyönä (2007) observed that participants with high memory spans used memorization strategies requiring a more demanding semantic elaboration, whereas low spans employed a less demanding rehearsal strategy.

However, it is not clear whether a person's WMC is defined by the strategies formulated for a specific task, or whether a person's WMC determines what specific strategy this person can use (Conway et al., 2005). Experiment 2 examines this issue by investigating whether low spans can successfully employ the more effective but also more demanding *Complete* strategy, and if use of the less effective, and less demanding *Position* strategy negatively effects high span's task performance.

3. Experiment 2

The results of Experiment 1 indicate that *Complete* strategy usage is more congruent with high span participants' dominant strategy selection and *Position* strategy use is more congruent with low span participants' strategy choice. However, it is unclear how the use of an incongruent strategy affects performance. Assuming that use of a more effective strategy enhances performance, the prediction is that low spans instructed to use the incongruent *Complete* strategy display lower error rates compared to low spans using a congruent *Position* strategy, whereas an incongruent strategy affects high span task performance negatively by increasing error rates. However, it is also possible, that the lower WMC of low spans does not allow them to utilize the more demanding *Complete* strategy effectively, thus impairing their performance.

Because the findings of Experiment 1 demonstrate more pronounced impact during moderate and difficult conditions of the primary task – pointing towards a potential ceiling effect, only these levels of task difficulty will be investigated. Furthermore, since the patterns between execution and planning errors were nearly identical in Experiment 1, analyses will focus on execution errors only.

3.1. Method

3.1.1. Participants

96 undergraduate students (51 females and 45 males) ranging in age from 18 to 28 ($M=21.2$, $SD=2.35$) participated in this experiment. Participants were categorized into 4 groups based on quartile values of absolute Aospan scores. Participants with scores in the lowest quartile (scores less than or equal to 23) were categorized as low spans, and participants with scores in the highest quartile (scores greater than or equal to 49) were categorized as high spans. The mean absolute Aospan score for the high span group was 59.17 ($n=24$; $SD=7.42$), while the low span group's mean score was 16.42 ($n=24$; $SD=4.31$). Thus, data of 48 undergraduate students (26 females and 22 males) ranging in age from 18 to 28 ($M=21.2$, $SD=2.35$) were included in the analyses.

Experiment 2 replicated the manipulations described in Experiment 1 with two exceptions. First, only a moderate and high task difficulty of the primary task was used, second, the present experiment manipulated strategy use of participants as a within subject factor, by instructing participants to employ the *Complete* or the *Position* strategy. As a result, there were two experimental conditions based on combinations of memory span and instructions: a combination of low span and *Position*, and of high span and *Complete* resulted in a congruent condition, whereas a combination of low span and *Complete* instruction, and a combination of high span and *Position* instruction resulted in an incongruent condition. All participants completed the experiment individually during the course of approximately 90 min and received credit towards a psychology course requirement. None of the participants from Experiment 2 participated previously in Experiment 1.

3.1.2. Materials

Materials used in this Experiment were identical to those used in Experiment 1 except for additional written instructions on strategy use.

3.1.3. Procedure

The procedure of this experiment was identical to Experiment 1, except that participants were instructed to apply a specific memory strategy for half of the trials of the navigation task, and the

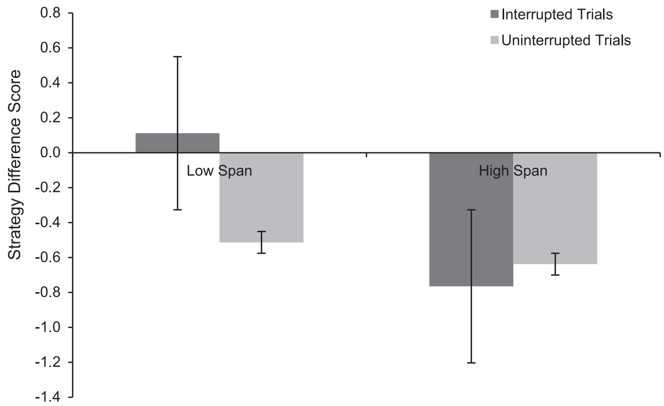

Fig.5. Strategy difference scores (complete-position) between interrupted and uninterrupted trials for each span group.

corresponding memory strategy for the second half. The sequence of instructed strategy use was counterbalanced across participants. Manipulation checks assured that participants followed the instructions. That is, participants in the *Complete* condition needed to recite all of the movement instructions to the experimenter, while participants in the *Position* condition recited only a series of numbers corresponding to the sequence of instruction implementation. The manipulation check was performed at the beginning of the execution phase. For example, if a participant intended to use the 3rd instruction, followed by the 1st instruction, and then the 6th instruction, they would recite to the experimenter the numbers 3–1–6 to identify the location of the instruction on the screen.

3.2. Results

3.2.1. Error rates

Overall, the execution error rates in the congruent condition for low spans in the moderate ($M=1.7$, $SD=0.59$) and difficult primary task conditions ($M=2.3$, $SD=0.57$) was larger than the execution error rate for high spans (moderate: $M=1.5$, $SD=0.39$; difficult: $M=1.6$, $SD=0.46$). For the incongruent condition, low spans had slightly lower execution error rates (moderate: $M=1.6$, $SD=0.61$; difficult: $M=2.1$, $SD=0.49$) than high spans (moderate: $M=1.8$, $SD=0.53$; difficult: $M=2.1$, $SD=0.62$). The differences in execution error rates were analyzed using a 2 (span group: high, low) × 2 (PT difficulty: moderate, difficult) × 2 (congruence: congruent or incongruent) mixed-model ANOVA. The statistical analysis revealed a significant main effect of PT difficulty $F(1,44)=8.365$, $p<.01$, $\eta_p^2=.160$, that was qualified by a span group × congruence interaction, $F(1,44)=11.642$, $p<.01$, $\eta_p^2=.209$ indicating that low spans benefitted from applying the Complete strategy.

To examine more specifically the impact of interruptions in the congruent and incongruent conditions a separate analysis was conducted for each congruence condition. For both analyses, a 2 (span group: high, low) × 2 (PT difficulty: moderate, difficult) ANOVA was performed. The analysis for the congruent condition revealed main effects of span group, $F(1,44)=11.142$, $p<.01$, $\eta_p^2=.202$, and PT difficulty, $F(1,44)=5.359$, $p=.03$, $\eta_p^2=.109$, replicating the results from Experiment 1. The same analysis for the incongruent condition revealed a main effect for PT difficulty only, $F(1,44)=5.862$, $p=.02$, $\eta_p^2=.118$.

3.2.2. Difference scores

To analyze the differential impact of the congruence manipulation difference scores of error rates were computed between congruent and incongruent memory strategy use. To calculate strategy difference scores, participant's error rates when using the Position strategy, were subtracted from error rates while applying the Complete strategy. Negative difference scores indicate that the Complete strategy produced lower error rates than the Position strategy. The only strategy difference score for which Complete did not result in an advantage over Position was for low spans during interrupted trials ($M=0.11$, $SD=0.64$) (see Fig. 5). The advantage was largest for the high span group during interrupted trials were error rates were smallest ($M=-0.77$, $SD=0.72$). Uninterrupted trials saw negative scores for both, low spans, ($M=-0.51$, $SD=0.60$), and high spans, ($M=-0.64$, $SD=0.77$). Analysis of the difference scores using a 2 (span group: high, low) × 2 (interruption presence: present, absent) ANOVA revealed a significant main effect due to interruption presence, $F(1,46)=4.533$, $p=.04$, $\eta_p^2=.090$, that was qualified by a significant span group × interruption presence interaction, $F(1,46)=10.341$, $p<.01$, $\eta_p^2=.184$.

3.3. Discussion

Experiment 2 investigated the effect of strategy use in high and low span participants on interrupted task performance. Strategy use was manipulated to determine whether low spans can apply the *Complete* strategy effectively. This experiment replicates results from Experiment 1 in that performance of low spans declines during interruptions. Additionally, Experiment 2 demonstrates that low span participants experienced an advantage by applying the *Complete* strategy; however, this advantage was limited to non-interrupted trials.

3.3.1. Error rates

The results for congruent trials yielded a similar pattern of execution errors to Experiment 1, such that low spans displayed higher execution error rates when dealing with a more difficult PT. This was in contrast to the high spans congruent usage of Complete strategy, which resulted in similar error rates across PT difficulty conditions. The presence of a span group × congruence interaction indicates that participants' performance was affected by the strategy manipulation. When low spans used the incongruent Complete strategy, they had lower error rates. Furthermore, high spans incongruent strategy usage resulted in error rates that were higher than low span incongruent strategy usage. Despite the fact that low spans performed similar to high spans, this finding favors a task dependent interpretation of memory span. Span groups in this experiment were based on independent Aospan measures and not selected based on the strategy a participant selected. Confirming results from previous research by Turner and Engle (1989), high spans chose a more effective strategy than low spans. However, contrary to Turner & Engle's implications, low spans were able to apply a more effective strategy. Nevertheless, these benefits were not present in all conditions.

3.3.2. Strategy difference scores

When considering overall performance, strategy selection affects memory performance under varying conditions differently. The results of Experiment 2 suggest that even by choosing a more effective strategy, improvements in performance for low span participants are still limited to cognitively less demanding tasks. In the presence of interruptions, low spans do not benefit from Complete strategy use. This finding indicates that in this task context the cognitive demand crossed a threshold that limits low spans level of maximum performance.

4. General discussion

The present paper contributes to the literature on the effects of interruptions on task performance by stressing the importance of individual differences in WMC (for similar, recent work see Bai et al., 2014). In addition, there are important implications for task design and HCI.

The results of the two experiments suggest that WMC is one critical limiting factor for task performance. It appears that some of these limitations can be overcome by encouraging the use of more effective, but also more effortful memory strategies (see also Beilock and DeCaro, 2007). However, these limitations are likely to present themselves at times of increased cognitive task demand.

Operating at the limits of working memory capacity can increase error rates and may lead to the selection of less effective strategies and methods of task execution. In Experiment 1, high span participants more readily adopted a cognitively demanding strategy, whereas low spans adopted a cognitively less demanding strategy. It appears, that participants selected strategies that accommodate their inherent WM limitations. For low span participants, this has a potentially self-handicapping effect, resulting in relatively impoverished performance. As demonstrated in Experiment 2, the analysis of individual differences allows identification of individuals who are more likely to employ a less effective strategy, and who benefit from use of alternative strategies.

In applied settings, human error can have significant consequences. As evidenced by the results of the experiments, interruptions increase execution and planning error rates. However, the present work also provides some guidance for potential solutions in applied settings.

First, the results point towards solutions that can be implemented to facilitate HCI. One solution is to reduce working memory load of operators while performing tasks. By providing checklists or guidance operator's memory of task steps can be supported and resumption of interrupted task facilitated (see e.g., Drews, 2013). In addition, systems could monitor operator activities and model the associated cognitive demand. Such approach, in combination with active interruption management that suppresses or permits interruptions (e.g., a system restart message or e-mail notification) based on modeled cognitive demand could reduce interruption's negative impact. To account for individual differences in WMC, the threshold used to suppress interruptions could be operator based. Second, the findings indicate that task performance can be increased by training some individuals to use more efficient strategies than the ones they would inherently apply. In safety critical industries, this approach could reduce human error. Third, as in many other contexts, selection of operators based on their WMC has the potential to reduce the likelihood of error further.

This work demonstrates that individual differences need to be included in our theories of how and to what extent interruptions affect human performance. This result is of importance in many applied contexts, because interruptions contribute to performance breakdowns, but well designed systems can minimize this impact.

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