Title	Interventions to reduce the negative consequences of interruptions on task performance and individual differences in working memory capacity
Author(s)	Zhang, Han; Kawashima, Tomoya; Shinohara, Kazumitsu
Citation	Applied Cognitive Psychology. 2023, 37(6), p. 1328-1340
Version Type	AM
URL	https://hdl.handle.net/11094/92585
rights	© 2023 John Wiley & Sons Ltd.
Note	

Interventions to reduce the negative consequences of interruptions on task performance and individual differences in working memory capacity

Han Zhang

Affiliation: Graduate School of Human Sciences, Osaka University

Email: zh443976311@gmail.com

ORCID ID: https://orcid.org/0000-0001-9810-0920

Tomoya Kawashima

Affiliation: Graduate School of Human Sciences, Osaka University

Email: kawashima-t@hus.osaka-u.ac.jp

ORCID ID: https://orcid.org/0000-0003-4634-3626

Kazumitsu Shinohara*

Affiliation: Graduate School of Human Sciences, Osaka University

Email: sinohara@hus.osaka-u.ac.jp

ORCID ID: https://orcid.org/0000-0002-7738-2073

*Corresponding author

Address: 1-2 Yamadaoka, Suita City, Osaka, 565-0871, Japan

Telephone Number: +81-6-6877-5111

Email: kaz.shinohara.hus@osaka-u.ac.jp

Running head: Interruption and Working Memory Capacity

Data availability statement: All raw data are included in the Supplemental Online Material associated with this article at https://osf.io/mqxkj/.

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

Ethics approval: Studies involving human participants were reviewed and approved by the Behavioral Research Ethics Committee of the Osaka University School of Human Sciences. The participants provided written informed consent.

Acknowledgments: The authors would like to thank Enago (www.enago.jp) for the English language review. The manuscript was drafted using DeepL Write and OpenAI ChatGPT. The AI generated text was read, revised and proofed by the authors. Han Zhang's current affiliation is the Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, Japan.

Author contributions: Han Zhang, Tomoya Kawashima, and Kazumitsu Shinohara contributed to the conception and design of the study. Han Zhang contributed to the data acquisition and wrote the first draft of the manuscript. All authors contributed to the statistical analysis; discussion, revision, and reading; and approved the final version of the manuscript.

Interventions to reduce the negative consequences of interruptions on task performance and individual differences in working memory capacity

Abstract

The current study aimed to investigate whether individual differences in working memory capacity (WMC) are associated with differences in subsequent task performance and whether intervention (interruption onset management) can reduce the negative effects of interruption. Experiment 1 compared task performances before and after interruptions and examined their relationship with WMC. The findings suggested that individuals with high levels of WMC were able to recover more quickly to the same level of performance as prior to the interruption. In Experiment 2, we examined whether manipulating the intervention could mitigate the detrimental effects of the interruption. The results demonstrated that individuals with high levels of WMC made fewer errors after the interruption, which were reduced by interventions for both low- and high-WMC groups. These results confirm that the impact of interruptions is proportional to differences in WMC, and interventions can reduce the negative impact of interruptions irrespective of WMC.

Keywords

interruptions, working memory capacity, individual differences, interruption onset management, resumption

1 INTRODUCTION

With the rapid development of technology in the information society, office work situations increasingly require multitasking, where several tasks are performed simultaneously (Kirchberg et al., 2015; Puranik et al., 2020). Multitasking frequently leads to inattention due to work interruptions, which leads to human errors and reduced efficiency and productivity (Adler & Benbunan-Fich, 2012; Buser & Peter, 2012). Especially in safety-critical work situations, such as aviation (Wilson et al., 2018) and medicine (Westbrook et al., 2018; Williams & Drew, 2017), errors can lead to serious damage, which threatens the safety and security of social systems. For this reason, researchers develop different types of interventions to reduce the negative consequences of interruptions (Guo et al., 2021).

Previous studies reported that working memory (WM) plays an important role in the cognitive processing of interruptions (Falkland et al., 2020; Klingberg, 2000; Meys & Sanderson, 2013). In addition, working memory capacity (WMC) was identified as an important predictor of interruptions: people with high levels of WMC can resume tasks quickly and accurately following interruptions compared to those with low levels of WMC (Foroughi, Malihi, et al., 2016;

Foroughi, Werner, et al., 2016). Therefore, it is crucial to consider individual differences in WMC while developing effective intervention methods for reducing the negative effects of interruptions.

This study first examined whether individual differences in WMC lead to divergence in subsequent task performance following an interruption. We further examined whether interruption onset management (i.e., providing an appropriate interval between alerts and interruptions to allow for preparation for interruptions) reduces the negative effects of interruptions and whether it occurs irrespective of individual differences in WMC.

1.1 THEORETICAL BACKGROUND

1.1.1 Time course of recovery after interruption

Figure 1 illustrates the phases in the flow of interruption and resumption (Trafton et al., 2003). In this timeline, two lag periods have been identified. Firstly, the time between the alert (e.g., a phone ringing) and the onset of the interruption task is defined as the *interruption lag*. Secondly, the time between the end of the interruption task and the first subsequent action is defined as the *resumption lag*. The resumption lag is a widely used metric for assessing the disruptive effect of interruption (Altmann & Trafton, 2004; Cades et al., 2011; Foroughi, Werner, et al., 2016; Monk, 2004; Trafton et al., 2003).

Altmann and Trafton (2007) have proposed that interruptions may have disruptive effects that extend beyond the first action after the interruption. They ascertained that not only does the first action require time to resume following an interruption, but subsequent actions also require time to fully recover from the interruption. To effectively manage the negative consequences of interruptions, it is critical to evaluate not only the performance immediately after the interruption, but also the performance of subsequent responses.

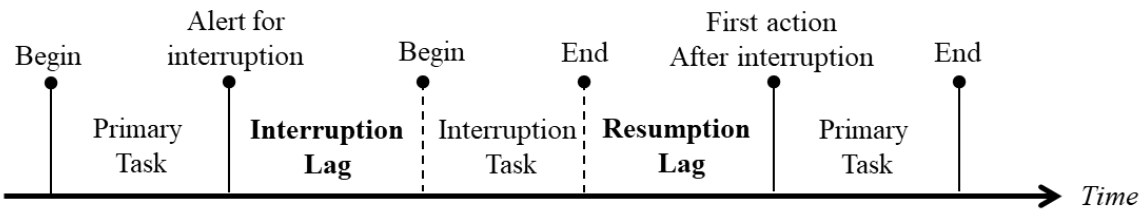

Figure 1. Time course of each phase of interruption and resumption involving a primary and an interruption task.

1.1.2 Relationship between interruptions and individual differences in WMC

Previous research has highlighted two necessary abilities for effectively managing interruptions (Baddeley et al., 2020; Baddeley & Hitch, 1974): firstly, the ability to perform the interruption task while retaining information about the primary task and secondly, the ability to resume the primary task after the interruption while suppressing the interference of the interruption. These abilities depend on the function of WM (Barrett et al., 2004; Shipstead et al., 2014; Unsworth & Engle, 2007). There is a strict limit on the amount of information that can be held in WM, and the amount of information that can be processed in WM at one time is called WM *capacity* (WMC). According to Foroughi, Werner, et al. (2016) and Foroughi, Malihi, et al. (2016), individuals with larger WMC were able to resume the interrupted primary task more quickly and correctly compared to those with smaller WMC. This result suggests that individuals with larger WMC resist interference more and maintain higher activation levels of the primary task goal compared with those with smaller WMC. However, previous studies have focused only on the first action immediately after the interruption (i.e., the resumption lag), and it is unclear whether subsequent task performance can also be influenced by the interruption. Therefore, the first motivation of the present study is to expand upon previous works on the resumption lag by examining whether individual differences in WMC exist not only immediately after the interruption but also in subsequent task performance.

1.1.3 Theoretical frameworks accounting for the cognitive processes of interruptions

To investigate the relationship between interruptions and individual differences in WMC, it is necessary to understand the theoretical framework of interruptions and individual differences in WMC. The memory-for-goals (MfG) model, proposed by Altmann and Trafton (2002), is an influential computational theoretical framework that has been used to explain the cognitive processes of interruptions. This model is based on the ACT-R theory, which explains individual differences in WMC in dual-task situations (Lovett et al., 1999). According to the MfG model, tasks are described as goals in WM, with each goal linked to a certain level of activation, and the most active current goal drives behavior. When an interruption occurs, the activation of the primary task goal decreases as the interruption task is processed, while the activation of the interruption task goal increases, thereby impeding the retrieval speed of the primary task and increasing the likelihood of errors. Therefore, maintaining the activation of the primary task goal and suppressing the interference from activation of the interruption task while retrieving the primary task goal are important abilities for successfully resuming the interrupted primary task (Foroughi, Werner, et al., 2016; Kane & Engle, 2003). Furthermore, these abilities have been posited to vary among individuals (Unsworth, 2016). Specifically, individual differences in WMC can be attributed to variations in the ability to actively maintain primary task-relevant information. Moreover, differences in the ability to suppress irrelevant information (interruption task interference) and retrieve primary task-relevant information from WM also contribute to variations in WMC. These sources of individual differences in WMC have been investigated in previous studies (Barrett et al., 2004; Shipstead et al., 2014; Unsworth, 2016; Unsworth & Engle, 2007).

1.1.4 Interventions for mitigating the negative effects of interruptions

In this study, we posit that WM plays an pivotal role in mitigating the deleterious effects of interruptions. Interruptions impose excessive cognitive demands on limited WMC and increase cognitive load. As a result, WM does not function properly in situations that require high cognitive loads, which results in lower performance in individual tasks (Falkland et al., 2020; Watanabe & Funahashi, 2015). However, since it is difficult to directly manipulate WM, we consider alternative approaches to mitigate the negative effects of interruptions.

According to Guo et al. (2021), effective interventions can mitigate the negative effects of interruptions by reducing the cognitive load on WMC and supporting the cognitive processes that underlie the resumption of interrupted tasks. Although they reported that three types of interventions (i.e., managing interruption lag, providing reminder cues, and training) were particularly effective in reducing the disruptive effects of interruptions, only interruption lag management can experimentally manipulate the disruptiveness of interruptions and reduce the disruptive effects of interruptions (Altmann & Trafton, 2002). Furthermore, the effectiveness of interruption lag management depends on the WM cognitive function involved in the cognitive processing of the interruption lag (Unsworth, 2016; Unsworth & Engle, 2007). In contrast, the other two interventions (i.e., providing reminder cues and training) do not involve the cognitive processes related to WM. Moreover, as Guo et al. (2021) pointed out, there are inadequate data to determine the positive effects of interruption lag management. Therefore, we focus on the intervention of managing interruption lag.

According to Altmann and Trafton (2002, 2004) and Trafton et al. (2003), the interruption lag provides an opportunity to prepare for the effective resumption of the primary task. During the interruption lag, participants prospectively prepare for resumption by encoding the primary task goal and generating useful cues to be utilized upon resuming the primary task after the interruption. The encoded goal can overcome the active interference of the interruption task goal, while the generated cues can aid in inferring the first action after the interruption. Additionally, participants retrospectively prepare by rehearsing the goal of the interrupted primary task. Retrospective rehearsal can increase the activation level of the interrupted primary task goal and prolong its maintenance in WM, thereby facilitating retrieval of the interrupted primary task information from memory during resumption (Trafton et al., 2003). Therefore, the cognitive processing of interruption lag is likely to impact the resumption of the primary task after the interruption. Furthermore, as discussed in the previous section, the strength of the activation level of the primary task goal, whether it is correctly encoded, and the availability of encoding cues are all closely related to individual differences in WMC. If the effectiveness of interruption onset management depends on individual differences in WMC, then designers need to be aware of these differences when planning and enhancing the effectiveness of interruption onset management interventions. Thus, the second motivation of this study is to examine the effectiveness of interruption onset management in attenuating the deleterious effects of interruptions, and whether this occurs independently of individual differences in WMC.

1.2 Objective of the study

There are two main objectives of the current study: (1) To examine whether individual differences in WMC result in variations in the subsequent task performance after the interruption; (2) To probe whether interruption onset management can reduce the negative effects of interruptions and whether this reduction occurs irrespective of individual differences in WMC.

2 EXPERIMENT 1

The main purpose of Experiment 1 was to examine whether individual differences in WMC lead to differences in subsequent task performance after interruption. Participants were classified into high- and low-WMC groups according to the scores of tests for measuring individual differences in WMC. We then compared their performances immediately after interruption and subsequent actions. The number of errors and reaction times were analyzed as an outcome measure. We hypothesized that the low-WMC group would produce more errors, longer resumption lags than those of the high-WMC group after interruption.

3 Method

3.1 Participants

The study recruited 30 undergraduate and graduate students for Experiment 1. The sample size was determined using G*Power 3, an a priori power analysis software (Faul et al., 2009). Based on a repeated measures analysis of variance (ANOVA), with a medium effect size of 0.25 (partial $\eta^2 = 0.06$), a significance value of 0.05, and a statistical power of 0.80, the sample size was calculated to be 10 per group. A total of 30 participants were determined based on a previous study that examined differences in cognitive function using grouping by WMC (Osaka & Osaka, 1994; Nishizaki & Osaka, 2004). The majority was recruited from a pool of students at Osaka University (*M* age = 22.9 years, *SD* = 1.90; male: 9, female: 21). All participants reported normal or corrected-to-normal visual acuity. This experiment was approved by the Osaka University Human Research Ethics Committee (HB020-086). Informed consent was obtained from each participant.

3.2 Tasks and materials

3.2.1 The primary task

The primary task was a computer-based, procedural task called the button-pressing task (Figure 2). The participants were required to click with the mouse on 26 alphabet buttons (22 mm in diameter) randomly displayed on a screen in the order of the alphabet. All trials began and ended by pressing the “A” and “Z” buttons, respectively. A 48-kHz tone (“ping-pong” sound) was presented for 1,000 ms when the button was pressed correctly. A different 48-kHz tone (“buh-boo” sound) was presented for 1,000 ms when the button was pressed incorrectly. The task would progress only if the correct button was pressed. To enable the participants to actively complete the test when resuming the interrupted primary task, the answer was displayed in red at the top of the screen when the incorrect button was pressed three times. The position of the alphabetical buttons on the screen was set randomly for each trial, and the distance between buttons was set at approximately 1 mm.

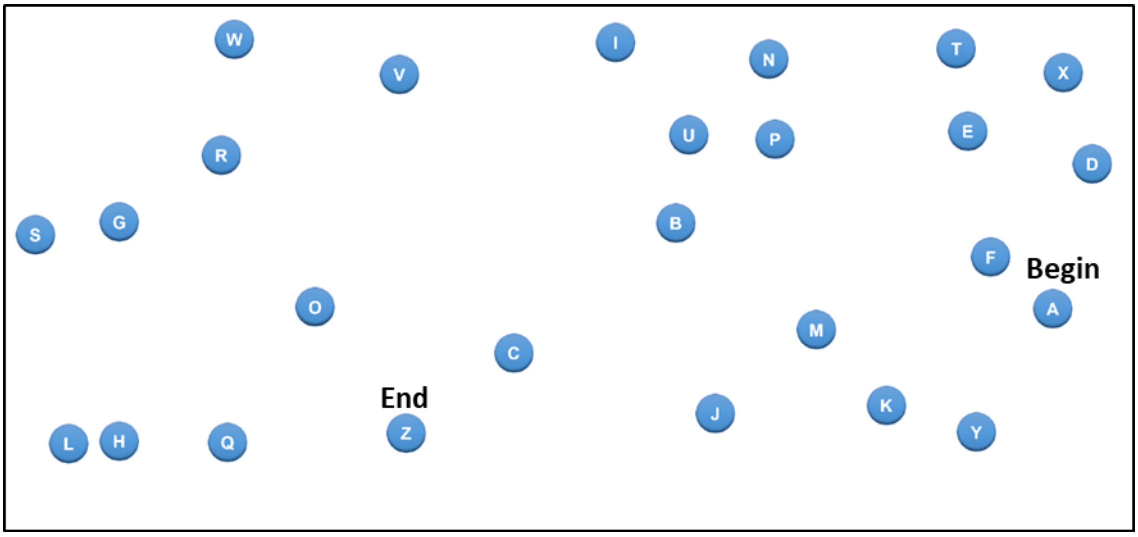

Figure 2. Example of the setup of the trial button-pressing task

3.2.2 The interruption task

The interruption task required participants to engage in a kana-hiroi test, which consists of grasping the content of a story written in kana with approximately 450 kana letters, while simultaneously selecting the following Japanese kana letters, namely, “あ(A),” “い(I),” “う(U),” “え(E),” and “お(O),” and erasing them using the backspace key. This test was created based on the kana-hiroi test included in the Clinical Higher Brain Function Assessment (Imamura, 2000). The narrative texts were selected from the Aozora Bunko digital library (https://www.aozora.gr.jp/). Different narrative sentences were presented in each trial. The participants selected as many target words as possible within 2-min without missing anything and while remembering the story. To ensure that the participants actively engaged in the interruption task, questions were presented at the end of the trial to assess understanding of the content of the narrative texts. Using Imamura (2000) as reference, questions were created according to the last sentence that the participants reached when reading the narrative texts. Immediately after the interruption task, the screen returned to the primary task, which was automatically resumed. Importantly, when returning to the primary task after an interruption, the screen was the same as before. Therefore, the participants needed to remember where they were interrupted to quickly resume the task without error.

3.3 Procedure

The participants were given a consent form to read and sign followed by an information sheet before participating in this experiment. After obtaining informed consent and demographic information, they were individually tested in the experiment. The task was developed using Python 3.8 programming language and presented on a 27-inch monitor (Iiyama G2773HS) at a resolution of 1,920 × 1,080 pixels.

First, WMC was measured using the OSPAN task (see Supplementary

Method). Next, the participants were given a short break then trained on the button-pressing and the kana-hiroi tasks to ensure their understanding of the experiment and to minimize potential learning effects. During the first practice trial, the participants were informed that the kana-hiroi task (interruption task) may appear at any time while performing the button-pressing task. All participants completed one practice trial while asking questions as needed. Finally, they completed 10 experimental trials (6 minutes per trial). The interruption task was triggered randomly when the awaited response to the primary task was between “I” and “S” and only once per trial. The participants were unaware of the timing of the presentation of the interrupted task during the primary task. After each trial, the participants answered questions to assess their understanding of the content of the story in the kana-hiroi test. The entire experimental session lasted approximately 1.5 h.

3.4 Measures

Two post-interruption dependent variables were measured, namely, errors and reaction times. After the interruption, only the first error was counted. Reaction times were calculated for each of the 10 trials, and only the first correct button was considered.

3.5 Results

3.5.1 Grouping of participants by WMC

Four participants were excluded, namely, one due to an error rate of more than 80% when returning to the primary task after the interruption and three with a median OSPAN score of 68. The final analysis consists of 26 participants (male: 8, female: 18, *M* age = 22.8 years, *SD* = 1.95). The 26 participants were divided into a high-WMC group (n = 13, M = 76.31, SD = 6.24), which consists of those with OSPAN scores higher than the median (*Med* = 68.00), and a low-WMC group (n = 13, M = 52.08, SD = 13.74). This method has been employed in previous studies (Klatt & Smeeton, 2021; Sörqvist et al., 2012). A significant difference in OSPAN scores between high- and low-WMC groups was observed ($t(24) = 5.79$, $p < .001$, $d = 2.20$). In addition, there was no significant difference in interrupt task accuracy between high- and low-WMC groups (see Supplementary Results).

3.5.2 Number of errors after interruptions

To investigate whether individual differences in WMC led to differences in subsequent task performance after the interruption, we first examined the number of errors made after interruptions using an unpaired *t*-test with WMC (high- and low-WMC groups) as the independent variable and number of errors as the dependent variable. The results indicated no significant differences between both groups (high-WMC: 24%; low-WMC: 21%: $t(24) = 0.47$, $p = .640$, $d = 0.18$). We also did not find a significant correlation between all OSPAN scores and the number of errors (after minus before interruption): $r(28) = -.05$, $p = .800$.

3.5.3 Reaction times

Figure 3 displays the mean reaction times for all conditions. We performed a 2 (WMC: high vs. low) × 5 (target stimulus position: last button before interruption [B1], first button after interruption [A1], second button after interruption [A2], third button after interruption [A3], and fourth button after interruption [A4]) mixed-model ANOVA. The main effect of WMC was not significant ($F(1, 24) = 3.49$, $p = .074$, $\eta_p^2 = 0.13$), but the main effect of the target stimulus position was significant ($F(4, 96) = 25.54$, $p < .001$, $\eta_p^2 = 0.52$). Multiple comparisons tests demonstrated that reaction times for A1 and A2 were longer than those for B1 (A1 > B1: $t(24) = 8.48$, $p < .001$, $d = 2.07$; A2 > B1: $t(24) = 3.75$, $p = .005$, $d = 0.99$). This result indicates that the reaction time was longer post-interruption compared with pre-interruption. Additionally, the reaction times of A3 and A4 were shorter than those of A1 and A2 (A3 < A1: $t(24) = 7.24$, $p <.001$, $d = 1.92$; A4 < A1: $t(24) = 9.29$, $p <.001$, $d = 2.25$; A3 < A2: $t(24) = 4.22$, $p =.002$, $d = 0.88$; A4 < A2: $t(24) = 4.29$, $p =.002$, $d = 1.14$). This result suggests that the response becomes progressively faster, indicating that there is a recovery process over time following the interruption.

Although the interaction between WMC and target stimulus location was not significant ($F(4, 96) = 2.64$, $p =.085$, $\eta_p^2 = 0.10$), planned comparisons to further analyze the simple main effects revealed that in the target stimulus location condition, there was a significant difference between high- and low-WMC groups at A1 ($t(120) = 3.48$, $p =.001$, $d = 3.05$). This also illustrated that the low-WMC group exhibited a significantly longer resumption lag (reaction time for the first button after interruption) than the high-WMC group. Moreover, we also found that there was a significant negative correlation between all OSPAN scores and reaction times ((A1 minus B1): $r(28) = -.37$, $p =.044$), indicating that the increase in OSPAN scores attenuated the time cost of resuming from an interruption. Additionally, in the WMC condition, the reaction times for A1 and A4 in the high-WMC group were longer and shorter than that for B1 ($t(24) = 4.12$, $p =.004$, $d =$

1.93) and A1 ($t(24) = 5.02$, $p <.001$, $d = 1.70$) respectively. Alternatively, for the low-WMC group, not only the reaction time of A1 was longer than that of B1 ($t(24) = 7.87$, $p <.001$, $d = 2.68$) but also the reaction time of A2 was longer than that of B1 ($t(24) = 3.01$, $p =.030$, $d = 1.10$). The reaction times of A3 and A4 were shorter than those of A1 and A2 (A3 < A1: $t(24) = 7.28$, $p <.001$, $d = 2.69$; A4 < A1: $t(24) = 8.12$, $p <.001$, $d = 2.74$; A3 < A2: $t(24) = 3.94$, $p =.004$, $d = 1.15$; A4 < A2: $t(24) = 3.13$, $p =.027$, $d = 1.16$). This result indicats that, in the subsequent task-related responses, the low-WMC group also took longer to fully recover from the interruption than the high-WMC group.

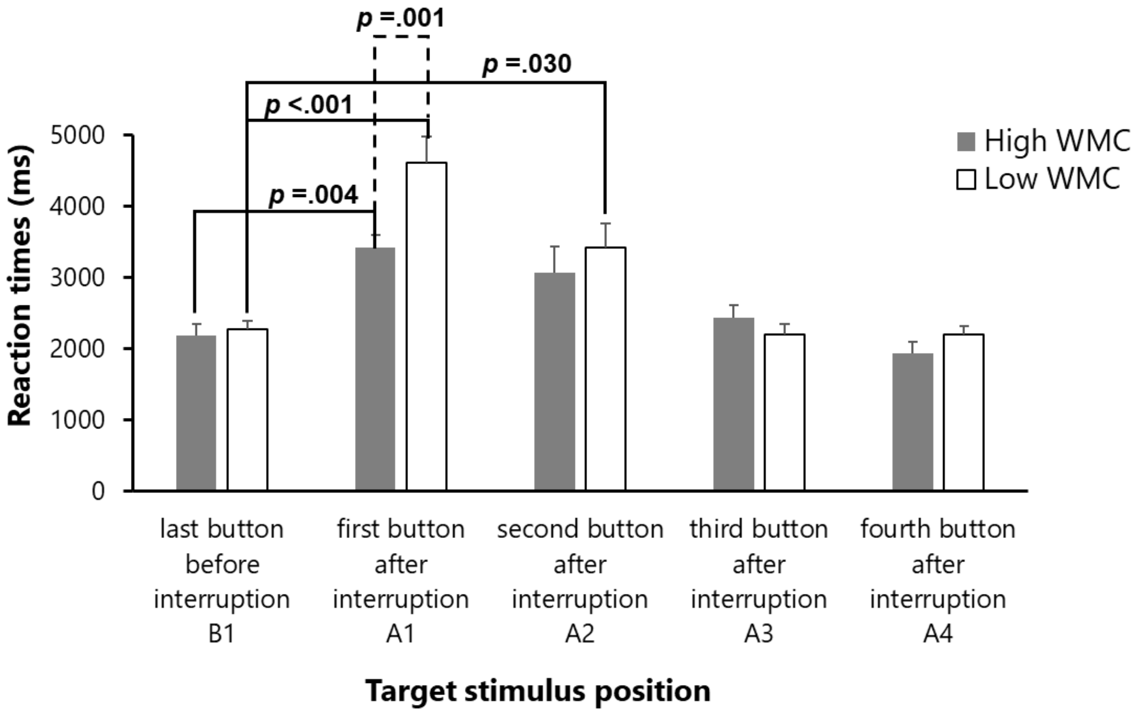

Figure 3. Individual differences in WMC in task performance after interruption. Error

bars represent standard errors.

3.6 Discussion

The objective of Experiment 1 was to determine whether individual differences in WMC led to a difference in subsequent task performance resumed following interruptions. In line with Foroughi, Werner, et al. (2016), the current study found that individuals with low-level WMC experienced longer resumption lags than those with high-level WMC. We found that the low-WMC group took longer to fully recover from the interruption in the subsequent task performance than the high-WMC group, indicating that individual differences in WMC can influence subsequent task performance after interruptions. These results indicate that individual differences in WMC may lead to divergence not only immediately after the interruption but also in subsequent task performance.

However, in terms of the number of errors after the interruption, in contrast to Foroughi, Malihi, et al. (2016), the study found no difference in task performance after an interruption according to individual differences in WMC. One possible reason for this result is that the primary task may have been extremely easy that it did not impose a sufficient cognitive load on WM. Therefore, the accuracy of primary task performance may be maintained irrespective of WMC. Alonso et al. (2021) report that errors are more likely to occur when interrupted during the execution of complex search tasks that require high-level WMC. To clearly examine whether individual differences in WMC led to a difference in post-interruption errors using a more difficult primary task is necessary.

4 EXPERIMENT 2

Experiment 2 had two objectives. First, to investigate whether individual differences in WMC result in a difference in the number of errors after interruption using a more difficult primary task that produces high levels of cognitive load. Second, to examine whether the negative effects of interruption could be mitigated by managing interruption onset, and whether it occurs irrespective of individual differences in WMC.

We hypothesized that: (1) individuals with low-WMC would make more errors following interruptions; (2) the interruption onset management can reduce the negative impact of interruptions and under the interruption onset management condition, individual differences in WMC are related to task performances following an interruption.

5 Method

5.1 Participants

The study recruited 34 undergraduate and graduate students. The majority were recruited from a pool of students at Osaka University (*M* age = 21.2 years, *SD* = 1.74; male: 8, female: 26). The sample size was calculated using G*Power 3, an a priori power analysis software (Faul et al., 2009) based on the results of Experiment 1, which assumes an effect size of 0.25, a significance value of 0.05, and a statistical power of 0.80. None of the participants participated in Experiment 1, and all reported normal or corrected-to-normal visual acuity. This experiment was approved by the Osaka University Human Research Ethics Committee (HB021-070). Informed consent was obtained from each participant.

5.2 Tasks and materials

5.2.1 The primary task

The primary task was designed as a button-pushing task using the alphabet, hiragana, and numbers, based on Part B of the Trail Making Test

(Sugimoto et al., 2014; Figure 4). Similar to Experiment 1, the participants pressed 26 buttons that appeared in random positions on the screen in the order of the alphabet, hiragana, and number (e.g., A–あ–0–B–い–1 …). The quantity of alphabet and hiragana buttons displayed on the screen was the same per trial (eight). The number of buttons with digits was also the same per trial with 10 buttons (from 0 to 9). The placement of the buttons on the screen was randomly changed across trials. To reduce the practice effect, the range of alphabet, hiragana, and numbers displayed at the top of the screen differed per trial, which began with the "A" button per trial and ended with the last numbered button. For example, Figure 4 illustrates that the first trial begins and ends by pressing the "A" and the last numbered button "6," respectively. Feedback from pressing the buttons was the same as that in Experiment 1. If the button was pressed incorrectly three times when resuming the interrupted primary task, the response was displayed at the top of the screen, which is identical to Experiment 1.

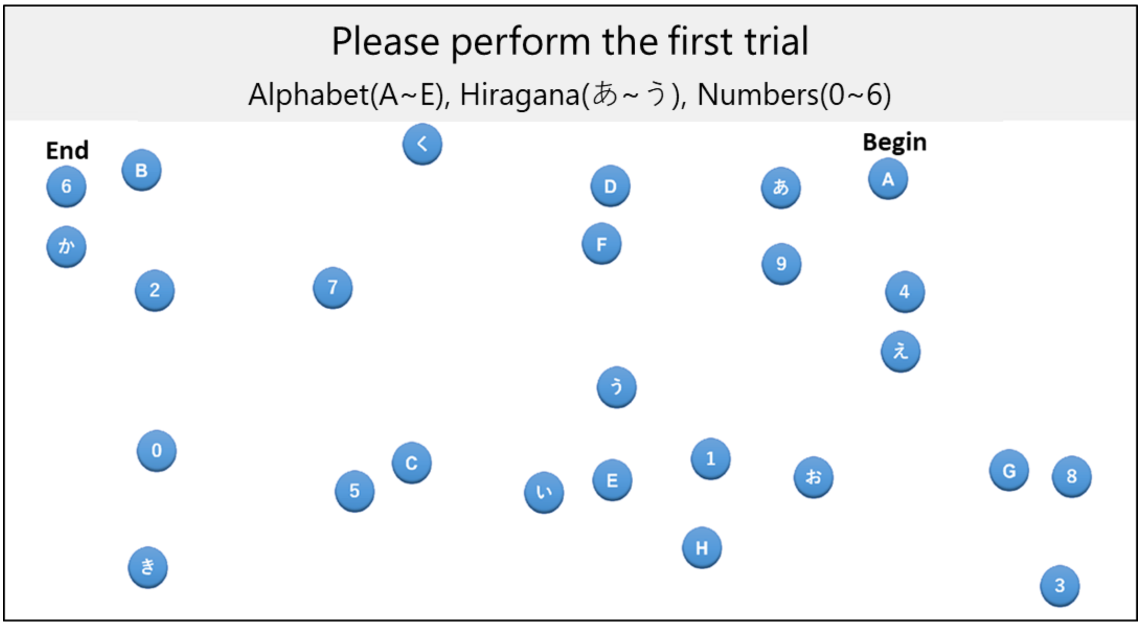

Figure 4. Example of a trial button-pushing task combined with the alphabet, hiragana, and numbers

5.2.2 The with and without interruption onset management conditions

In the interruption onset management condition, a notification "You have a new message" appeared in the top-right corner of the screen as an alert of the pending interruption (Figure 5), while the state of the display remained displayed during the interruption lag. Furthermore, previous studies (Altmann & Trafton, 2007; Iqbal & Bailey, 2005; McFarlane & Latorella, 2002; Sloane et al., 2022; Trafton et al., 2003) suggest that it is preferable to entrust the control of the interruption onset to the participant as they can be adequately prepared for resumption of the primary task before the interruption, thus reducing the burden at resumption and facilitating resumption of the primary task. Therefore, participants were instructed that:

During work on the primary task, a notification pop-up may appear in the top-right corner of the screen. Once the notification has popped up, work on the primary task is no longer possible. Please click the “OK” button when you think it is a good time to move to start the interruption task.

Under the condition without interruption onset management, the primary task screen (and its current its state) was replaced by the interruption task screen when the interruption occurred (similar to Experiment 1). Under both conditions at the start of the interruption task (i.e., the end of the interruption lag), the primary task screen (and its current state) was replaced with the interruption task display. The interruption task and WM measurement task were the same as those in Experiment 1.

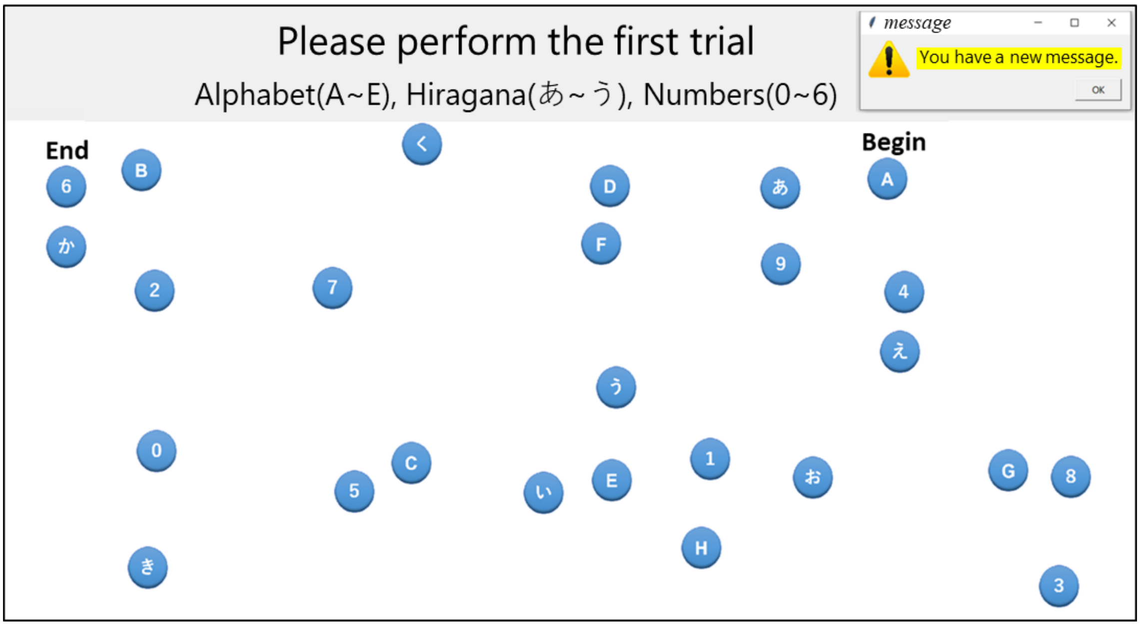

Figure 5. Example of a trial showing the interruption onset management condition

5.3 Procedure

All procedures were essentially the same as those in Experiment 1. All participants initially engaged in one practice trial to orient them to the experiment. A session began with a training period, in which the participants learned how to perform both tasks separately and were provided an example of how the computer would switch them from one task to another and back to the primary task. In contrast to Experiment 1, the participants could decide when to start the interruption task in the interruption onset management condition. The first and second halves of the participants first completed the interruption onset management (five trials) and without interruption onset management (five trials) conditions, respectively.

5.4 Measures

Three dependent variables were measured, namely, error, reaction time, and interruption lag. The calculations of errors and reaction times were the same as those in Experiment 1.

5.5 Results

5.5.1 Grouping of participants by WMC

Nine participants were excluded from the analysis: two due to error rates of more than 80% when returning to the primary task after the interruption, three due to the lack of correct responses before and after the interruption task, and four with a median OSPAN score of 74. The final sample consisted of 25 participants (male: 7, female: 18, M age = 21.0 years, SD = 1.57). The 25 participants were divided into a high-WMC group (n = 13, M = 84.23, SD = 7.03), which consists of those with OSPAN scores higher than the median (Med = 74.00), and a low-WMC group (n = 12, M = 60.42, SD = 11.41). This method has been employed in previous studies (Klatt & Smeeton, 2021; Sörqvist et al., 2012). A significant difference in OSPAN scores between high- and low-WMC groups was observed ($t(23) = 6.34$, $p < .001$, $d = 2.46$). Additionally, there was no significant differences in interruption task accuracy based on individual differences in WMC (see Supplementary Results).

5.5.2 Number of errors after interruptions

We performed a 2 (WMC: high vs. low) × 2 (target stimulus position: last button before vs. first button after interruption) × 2 (interruption onset management condition: with vs. without) mixed-model ANOVA. The main effect of WMC was significant ($F(1,23) = 5.67$, $p = .026$ $\eta_p^2 = 0.20$), which indicated that the number of errors of the low-WMC group was higher than that of the high-WMC group. In addition, the main effect of target stimulus position was significant ($F(1,23) = 17.85$, $p < .001$, $\eta_p^2 = 0.44$), which indicated that the number of errors was higher in post-interruption than in pre-interruption. We also found a significant interaction between target stimulus location and interruption onset management condition ($F(1,23) = 5.58$, $p = .027$, $\eta_p^2 = 0.20$). Further analysis of the simple main effects revealed that, in the condition without interruption onset management, more errors occurred on the first button after the interruption than before ($F(1,23) = 23.14$, $p < .001$, $\eta_p^2 = 0.50$). In addition, at the first button position after interruption, more errors occurred under the without interruption onset management condition than those under the interruption onset management condition (F(1,23) = 4.70, p =.040, η_p^2 = 0.17; Figure 6).

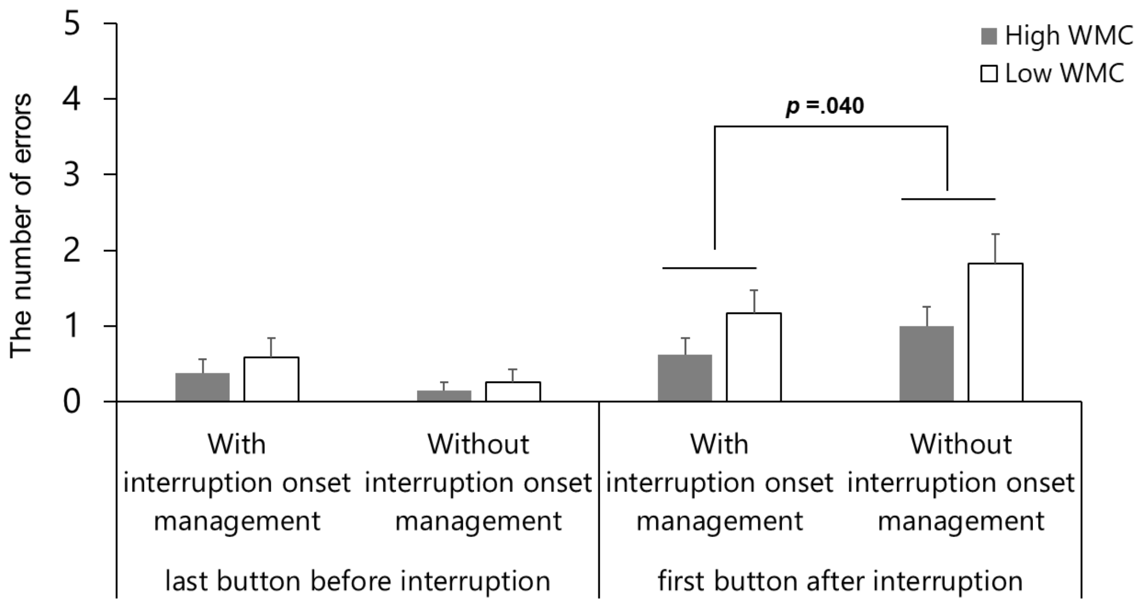

Figure 6. Differences in the number of errors after an interruption according to with and without interruption onset management conditions. Error bars represent standard errors.

5.5.3 Reaction times

To investigate whether the effects of individual differences in WMC found in Experiment 1 are also reflected in Experiment 2 (where the difficulty of the primary task is increased), we performed a 2 (WMC: high vs. low) × 2 (interruption onset management condition: with vs. without) × 5 (target stimulus position: last button before interruption [B1], first button after interruption [A1], second button after interruption [A2], third button after interruption [A3], fourth button after interruption [A4]) mixed-model ANOVA A (see Table 1). We excluded the data of trials where B1, A1, A2, A3, and A4 were incorrect (136 trials, 45% of all trials). The remaining trials (164 trials, 55%) were analyzed. ANOVA displayed no significant differences in WMC ($F(1, 23) = 1.40$, $p = .248$, $\eta_p^2 = 0.06$), interruption onset management condition ($F(1, 23) = 0.85$, $p = .365$, $\eta_p^2 = 0.04$), and interaction effects ($F(1, 23) = 1.88$, $p = .184$, $\eta_p^2 = 0.08$). We found a significant difference in the target stimulus position ($F(4, 92) = 17.32$, $p < .001$, $\eta_p^2 = 0.43$). Multiple comparison tests revealed that reaction times in B1 was shorter than those in A1 and A2 (B1 < A1: $t(23) = 5.02$, $p < .001$; B1 < A2: $t(23) = 6.85$, $p < .001$) and that reaction times in A1 and A2 were longer than those in A3 and A4 (A1 > A3: $t(23) = 3.83$, $p = .003$; A1 > A4: $t(23) = 4.64$, $p < .001$; A2 > A3: $t(23) = 6.19$, $p < .001$; A2 > A4: $t(23) = 5.02$, $p < .001$). These results indicate that after the interruption, the reaction time was longer than that pre-interruption for both groups.

Table 1. Three-way ANOVA for WMC, Interruption onset management condition, and

Target stimulus position

Source of variance	SS	df	MS	F	p	η_p^2
WMC	29303417.06	1	29303417.06	1.40	0.248	0.06
Interruption onset management condition	3037733.27	1	3037733.27	0.85	0.365	0.04
WMC × Interruption onset management condition	6702135.31	1	6702135.31	1.88	0.184	0.08
Target stimulus position	425171932.81	4	106292983.20	17.32	0.0000***	0.43
WMC × Target stimulus position	9859051.08	4	2464762.77	0.40	0.807	0.02
Interruption onset management condition × Target stimulus position	20125290.85	4	5031322.71	0.80	0.531	0.03
WMC × Interruption onset management condition × Target stimulus position	19195683.21	4	4798920.80	0.76	0.555	0.03
Total	2224899745.25	249	8935340.34			

***p < .001

5.5.4 Relationship between interruption and resumption lags

To examine whether the management of interruption onset could reduce the adverse effects after the interruption, the study calculated for the correlation between interruption and resumption lags (Figure 7). Data from one participant were omitted at standard deviation (3SD). The results exhibited a significant negative correlation ($r(31) = -.42$, $p = .016$), which indicated that the longer the interruption lag, the shorter the resumption lag. This finding was consistent even after excluding the 9 participants ($r(23) = -.47$, $p = .019$).

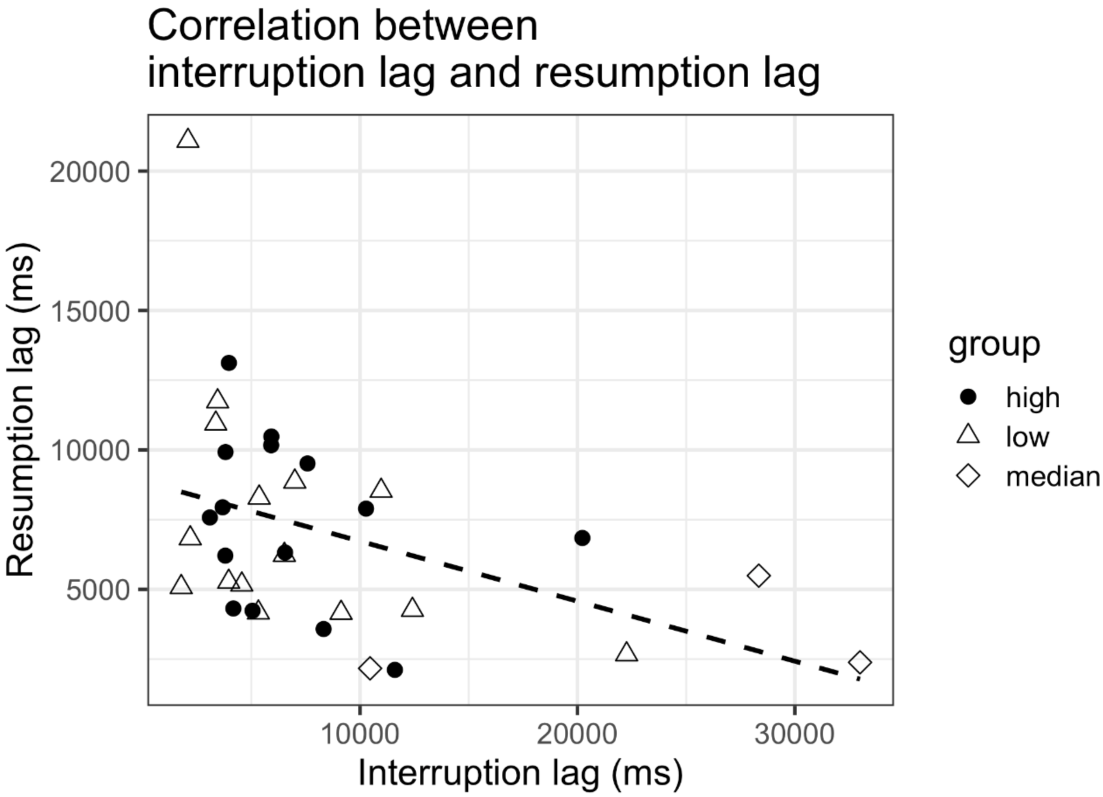

Figure 7. Correlation between interruption lag and resumption lag

5.6 Discussion

The objective of Experiment 2 was to determine whether individual differences in WMC is related to errors after interruptions and to examine whether the adverse effects of interruption can be mitigated by managing interruption onset, irrespective of individual differences in WMC. As hypothesized, the results demonstrated that individuals with low-level WMC made more errors following interruptions than those with high-level WMC. The current data are consistent with the findings of Foroughi, Malihi, et al. (2016), which revealed a moderate negative relationship (r = −.35) between WMC and number of errors made following interruptions. Specifically, as the WMC increased, the number of errors made after interruptions decreased. Furthermore, as predicted, fewer errors occurred in the interruption onset management condition than in the condition without interruption onset management. This result suggests that inserting interruption lag before an interruption can mitigate the adverse effects of interruptions. However, contrary to our hypothesis, we found that interruption onset management can reduce the negative impact of interruptions irrespective of WMC. This finding was inconsistent with our predictions based on the nature of individual differences in WMC (Shipstead et al., 2014; Unsworth, 2016; Unsworth & Engle, 2007) and previous interruption lag studies (Altmann & Trafton, 2004; Trafton et al., 2003). One possible explanation for the discrepancy between our results and hypothesis is that in our experiments, participants could decide when to start the interruption task, allowing them enough time to prepare to effectively resume the primary task after the interruption. Although no difference in the interruption lag was observed between high- and low-WMC groups, possibly due to the ceiling effect (high-WMC: 7386ms; low-WMC: 6922ms: $t(23) = 0.22$, p =.825, d = 0.09), we assume that even the low-WMC group was able to effectively resume the primary task by encoding and rehearsing the primary task goal during the interruption lag. In contrast, in previous studies, the duration of interruption lag was predetermined, and participants could not control when to start the interruption task (Altmann & Trafton, 2007; Trafton et al., 2003). This may explain why the current study found no difference in performance between WMC groups after the interruption recovery.

Furthermore, data pointed to a negative relationship between interruption and resumption lags (Figure 7). Specifically, resumption lag after interruptions decreased with the increase in interruption lag. This indicates that participants utilized the interruption lag to prepare themselves for later resumption. Therefore, Our result suggests that allowing participants to control the duration of the interruption lag may be an effective intervention method for reducing the negative consequences of interruptions.

With regard to the reaction time after the interruptions, the study found no significant differences under the WMC and interruption onset management conditions. One possible reason for this result is that the primary task in Experiment 2 was more complex and difficult compared with that in Experiment 1. The participants could not remember where the primary task was interrupted irrespective of individual differences in WMC when returning to the primary task after the interruption due to the extreme difficulty of the primary task. Another possible reason is that the participants were instructed as follows: “When returning to the primary task, even if you do not remember which button was pressed before the interruption, try to press a button. The answer will be displayed in red at the top of the screen after incorrectly pressing a button three times.” Many participants could not remember where they left off when returning to the primary task. Therefore, they initially guessed by pressing a random button.

6 GENERAL DISCUSSION

The overall objective of this research was to examine whether individual differences in WMC are associated with differences in subsequent task performance following interruptions and whether interruption onset management can reduce the negative consequences of interruptions irrespective of WMC. Experiment 1 indicated that individual differences in WMC influenced task performance not only immediately after the interruption but also in subsequent task performance, extending previous works that have only demonstrated individual differences in WMC immediately after the interruption (Foroughi, Malihi, et al., 2016; Foroughi, Werner, et al., 2016). Experiment 2 extended the finding of Experiment 1 in that the low-WMC group made more errors than the high-WMC group. We further found that interruption onset management in both WMC groups reduced the negative effects of interruption. Togerther, our results demonstrated that the impact of interruption is related to differences in WMC. Concurrently, irrespective of WMC, it is feasible to reduce the adverse effects of interruptions through interruption onset management. This result provides evidence to support the positive effects of interruption lag management.

6.1 Impact of individual differences in WMC on subsequent task performance after interruption

The study found that participants with high-level WMC resumed the interrupted primary task faster and more accurately than participants with low-level WMC. This finding is consistent with previous studies that individual differences in WMC are related to variations in performance immediately after interruption (e.g., Foroughi, Malihi, et al., 2016; Foroughi, Werner, et al., 2016). Although these previous works measured performance in terms of “just after the interruption” (e.g., resumption lag), the present study focused on temporal changes in subsequent task performance after interruption. To the best of our knowledge, the current study is the first to illustrate individual differences in WMC not only immediately after the interruption but also in subsequent task performance. This finding suggests that when the participants resume the interrupted primary task, the level of activation of the to-be-resumed primary task goal undergoes a time-dependent recovery process and proceeds over time (Altmann & Trafton, 2007). This result could be considered a new insight into individual differences in WMC during task interruption.

The study demonstrated that, although the participants resumed the interrupted primary task, the high- and low-WMC groups took longer time and generated more errors during the resumption of the first button after the interruption. This result may be due to the fact that the activation level of the primary task goal decreased while participants were engaged in the interruption task and retrieved the goal of the primary task to resume the task in the presence of interruption task interference (Monsell, 2003; Unsworth & Engle, 2007). This effect was no longer observed in the high-WMC group after resuming the first button. However, it continued to exist in the low-WMC group. This is probably because the recovery process is possible through associative links between retrieval cue recoveries and the to-be-resumed goal (Altmann & Trafton, 2002). Specifically, compared to the high-WMC group, the low-WMC group was not able to maintain the task-relevant information in a highly active state, and could not select the appropriate information to encode and generate effective cues. Therefore, when returning to the primary task, the low-WMC group required more time to retrieve the task goal and could not rely on effective cues to resume, resulting in slower and less accurate recall compared to the high-WMC group (Unsworth, 2016; Unsworth & Engle, 2007).

6.2 Interruption onset management reduces the negative effects of interruption

The study found that using intervention in the form of interruption onset management could significantly reduce the negative effects of interruptions for both groups. Specifically, interruption onset management was found effective in reducing resumption lag (reaction time for the first button after an interruption) and errors. The data support predictions made by the MfG model (Altmann & Trafton, 2002), which predicts that interruption lag is a critical period to prepare for the resumption of the primary task. According to previous studies, if the interruption lag is prolonged, then we predict that the participants can (1) repeatedly rehearse or strengthen the primary task goal and (2) encode retrieval cues (related to the primary task), which, thereby, boosts the activation level of the suspended goal of the primary task. Furthermore, this study employed a procedural primary task, and the execution of procedural tasks depends on the intact associative links between task steps. Accordingly, we predict that the primary task goal will be easily retrieved at a later time, because the association between the primary task goal and the retrieval cue is created and strengthened (Altmann & Trafton, 2002; Hodgetts & Jones, 2006). As predicted, resumption lag decreases during longer interruption lags in Experiment 2 (Figure 7). This indicates that interruption onset management is an effective intervention for reducing the negative effects of interruptions.

7 Limitations

This study has its limitations. Although we demonstrated that individual differences in WMC are associated with differences in task performance after interruption, the sample size was small and the gender distribution was unbalanced, with 73% of participants being female. The gender imbalance may have influenced the effectiveness of the interruption (Kalgotra et al., 2019). Therefore, the study would benefit from a larger sample with a more balanced gender distribution to increase the generalizability of the results. Additionally, the high similarity between the WMC measurement task and the experimental task may have contributed to the observed results, and using alternative WMC measurement tasks to replicate the findings would be advisable. The second limitation of our study is that the current study only examined a computer-based procedural primary task and the “management of interruption lag” as an intervention. As reported by Guo et al. (2021), the effectiveness of interventions requires further investigation, because it depends on the type of interrupted primary task (e.g., decision-making, or problem-solving tasks). Furthermore, although we examined whether interruption onset management mitigates the detrimental effects of interruptions, we did not specifically distinguish the role of interruption alerts and long interruption lags in this context. Investigating this could provide valuable insights into their influence on cognitive processes during the interruption lag and it have significant implications for the design of interruption onset management systems and the optimization of overall work efficiency. Finally, interruptions are a real-world problem that cannot sufficiently be examined only in laboratory studies. Thus, investigating the effects of WMC and the effectiveness of intervention methods on interruptions in real-life work environments is necessary. Doing so will enable the current study to confirm the validity of its findings and to discover the factors that influence interruptions that were not examined in this study. For example, the effects of an intervention in safety-critical work situations help workers remember information related to the task they were working on before interruption.

8 Practical contributions

Interruptions place a heavy burden on WM and are inherently disruptive in nature. For this reason, although interruptions are considered inevitable, the work environment should be designed to reduce interruptions as much as possible. The current study found that individuals with high-level WMC were highly resistant to interruptions; thus, considering WMC as one of the modern occupational aptitudes is possible. In addition, a great need exists for effective intervention methods for mitigating the effects of interruptions. Developing technologies to support workers based on the findings of this study is important for a safer and more productive work environment. For instance, one can imagine an AI system that manages interruption lag. It can track the activity status of workers throughout the process and predict the occurrence of interruption. In addition, we demonstrate that inserting a brief delay before an interruption mitigates its negative effects. Therefore, when an interruption comes, the system can prevent workers from being interrupted immediately by determining their current working status (e.g., WM load) and selecting the appropriate time to alert them of the interruption. At the same time, an interruption lag is provided, such that they can prepare for the resumption of the interrupted task.

9 Conclusion

This study examined differences in subsequent task performance after interruptions due to individual variations in WMC and whether interruption onset management could mitigate the negative effects of interruptions. The results confirmed that the effects of interruption were related to differences in WMC: those with low-level WMC recovery more slowly compared with those with high-level WMC. We further found that interruption onset management can minimize the negative effects of interruptions for both groups. The management of interruption lag may help ensure efficient and correct performance following interruptions by improving work performance in safety-critical environments.

References

Adler, R. F., & Benbunan-Fich, R. (2012). Juggling on a high wire: multitasking effects on performance. *International Journal of Human-Computer Studies, 70*(2), 156–168.

Alonso, D., Lavelle, M., & Drew, T. (2021). The performance costs of interruption during visual search are determined by the type of search task. *Cognitive Research: Principles and Implications, 6*(1), 1–11.

Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: an activation-based model. *Cognitive Science, 26*(1), 39–83.

Altmann, E. M., & Trafton, J. G. (2004). Task interruption: resumption lag and the role of cues. *Proceedings of the 26th Annual Conference of the Cognitive Science Society,* 43–48.

Altmann, E. M., & Trafton, J. G. (2007). Timecourse of recovery from task interruption: Data and a model. *Psychonomic Bulletin and Review*, *14*(6), 1079–1084.

Baddeley, A. D., Eysenck, M. W., & Anderson, M. C. (2020). Memory. (3th ed., pp. 71–105). New York: Routledge Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). New York: Academic Press.

Barrett, L. F., Tugade, M. M., & Engle, R. W. (2004). Individual differences in working memory capacity and dual-process theories of the mind. *Psychological Bulletin*, *130*(4), 553–573.

Buser, T., & Peter, N. (2012). Multitasking. *Experimental Economics, 15*(4), 641–655.

Cades, D. M., Boehm-Davis, D. A., Trafton, J. G., & Monk, C. A. (2011). Mitigating disruptive effects of interruptions through training: what needs to be practiced? *Journal of Experimental Psychology. Applied*, *17*(2), 97–109.

Falkland, E. C., Wiggins, M. W., & Westbrook, J. I. (2020). Cue utilization differentiates performance in the management of interruptions. *Human Factors, 62*(5), 751–769.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G* Power 3.1: tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160.

Foroughi, C. K., Malihi, P., & Boehm-Davis, D. A. (2016). Working memory capacity and errors following interruptions. *Journal of Applied Research in Memory and Cognition, 5*(4), 410–414.

Foroughi, C. K., Werner, N. E., McKendrick, R., Cades, D. M., & Boehm-Davis, D. A. (2016). Individual differences in working-memory capacity and task resumption following interruptions. *Journal of Experimental Psychology: Learning Memory and*

Cognition, 42(9), 1480–1488.

Guo, J., Chen, T., Xie, Z., & Or, C. K. (2021). Effects of interventions to reduce the negative consequences of interruptions on task performance: a systematic review, meta-analysis, and narrative synthesis of laboratory studies. *Applied Ergonomics, 97*, 103506.

Hodgetts, H. M., & Jones, D. M. (2006). Contextual cues aid recovery from interruption: the role of associative activation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(5), 1120–1132.

Imamura, Y. (2000). Clinical higher brain function assessment manual 2000. Shinkoh Igaku Shuppan.

Iqbal, S. T., & Bailey, B. P. (2005). Investigating the effectiveness of mental workload as a predictor of opportune moments for interruption. *CHI'05 extended abstracts on Human factors in computing systems*, 1489–1492.

Kalgotra, P., Sharda, R., & McHaney, R. (2019). Don’t disturb me! Understanding the impact of interruptions on knowledge work: An exploratory neuroimaging study. *Information Systems Frontiers*, *21*(5), 1019-1030.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to stroop interference. *Journal of Experimental Psychology: General, 132*(1), 47–70.

Kirchberg, D. M., Roe, R. A., & Van Eerde, W. (2015). Polychronicity and multitasking: a diary study at work. *Human Performance, 28*(2), 112–136.

Klatt, S., & Smeeton, N. J. (2021). Spatial Separation and Working Memory Capacity Affect Selective Visual Attention in the Periphery. *Frontiers in Psychology*, *12*, 692963.

Klingberg, T. (2000). Limitations in information processing in the human brain: neuroimaging of dual task performance and working memory tasks. *Progress in Brain Research, 126*, 95–102.

Lovett, M. C., Reder, L. M., & Lebiere, C. (1999). Modeling working memory in a unified architecture: An ACT-R perspective. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control, 506*,135–182. Cambridge, England: Cambridge University Press.

McFarlane, D. C., & Latorella, K. A. (2002). The scope and importance of human interruption in human-computer interaction design. *Human-Computer Interaction*, *17*(1), 1–61.

Meys, H. L., & Sanderson, P. M. (2013). The effect of individual differences on how people handle interruptions. *Proceedings of the Human Factors and Ergonomics*

Society, 57(1), 868–872.

Monk, C. A. (2004). The Effect of Frequent versus Infrequent Interruptions on Primary Task Resumption. *Proceedings of the Human Factors and Ergonomics Society. Annual Meeting Human Factors and Ergonomics Society. Meeting*, *48*(3), 295–299.

Monsell, S. (2003). Task switching. *Trends in cognitive sciences*, *7*(3), 134-140.

Nishizaki, Y., & Osaka, M. (2004). Text comprehension and individual differences in working memory: The different contributions of the storage and the retrieval processing. *The Japanese Journal of Psychology, 75*(3), 220-228.

Osaka, M., & Osaka, N. (1994). Working memory capacity related to reading: Measurement with the Japanese version of reading span test. *The Japanese Journal of Psychology, 65*(5), 339–345.

Puranik, H., Koopman, J., & Vough, H. C. (2020). Pardon the interruption: an integrative review and future research agenda for research on work interruptions. *Journal of Management, 46*(6), 806–842.

Shipstead, Z., Lindsey, D. R. B., Marshall, R. L., & Engle, R. W. (2014). The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control. *Journal of Memory and Language*, *72*, 116–141.

Sloane, J. F., Newell, B. R., Liang, G., & Donkin, C. (2022). The Mazing Race: Effects of Interruptions and Benefits of Interruption Lags in a Novel Maze-Like Decision-Making Paradigm. *Journal of Experimental Psychology: Applied*.

Sörqvist, P., Nöstl, A., & Halin, N. (2012). Working memory capacity modulates habituation rate: Evidence from a cross-modal auditory distraction paradigm. *Psychonomic Bulletin & Review*, *19*(2), 245-250.

Sugimoto, S., Okuma, O., Koyama, T., Sakuma, H., KOMIYAMA, J., Isami, O., Akina, K. (2014). Relationship between a simplified version of the trail making test and the Japanese version of the trail making test. *Rigakuryoho Kagaku, 29*(3), 357–360.

Trafton, J. G., Altmann, E. M., Brock, D. P., & Mintz, F. E. (2003). Preparing to resume an interrupted task: Effects of prospective goal encoding and retrospective rehearsal. *International Journal of Human Computer Studies, 58*(5), 583–603.

Unsworth, N. (2016). The many facets of individual differences in working memory capacity. In B. H. Ross (Ed.), *Psychology of Learning and Motivation, 65,* 1–46.

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: active maintenance in primary memory and controlled search from secondary memory. *Psychological Review, 114*(1), 104–132.

Watanabe, K., & Funakashi, S. (2015). The role of prefrontal cortex in dual-task processing. *Primate Research, 31*(2), 87–100.

Westbrook, J. I., Raban, M. Z., Walter, S. R., & Douglas, H. (2018). Task errors by emergency physicians are associated with interruptions, multitasking, fatigue and working memory capacity: a prospective, direct observation study. *BMJ Quality and Safety*, *27*(8), 655–663.

Williams, L. H., & Drew, T. (2017). Distraction in diagnostic radiology: how is search through volumetric medical images affected by interruptions? *Cognitive Research: Principles and Implications, 2*(1), 1–11.

Wilson, M. D., Farrell, S., Visse, T. A. W., & Loft, S. (2018). Remembering to execute deferred tasks in simulated air traffic control: the impact of interruptions. *Journal of Experimental Psychology: Applied, 24*(3), 360–379.