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Susceptibility to Visual Interference in Working Memory: Different Results Depending on the Prioritization Mode?

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Among several items held in working memory, an item can be prioritized by focusing attention on it. Some studies found that an item in the focus of attention is better protected from interference than other items in working memory. Others have found that a prioritized item is particularly vulnerable to interference. These two groups of studies have used different ways to study information in the focus of attention in working memory. Protection for the prioritized item has been found when a retro-cue has been used to direct attention to this item, whereas particular vulnerability has been observed for the last-presented item of a serially presented list, which is often assumed to remain in the focus of attention during the retention interval. As these two methods might represent distinct forms of prioritization, we examined whether these two prioritization modes result in opposing results. To do so, we sequentially presented four to-be-memorized colored shapes and probed memory with a recall task. We varied the presentation of interfering visual stimuli following the last list item. In half of the trials, we indicated which item was most likely to be probed using a retro-cue (Experiments 1 and 5) or a precue (Experiments 2–4). We observed some evidence for the last-presented item being particularly vulnerable to visual interference but only in specific task situations. Generally, we observed that memory items were equally vulnerable to visual interference regardless of their priority state in working memory and regardless of the prioritization mode used.

Public Significance Statement

When attention is focused on specific information in working memory, this information is assumed to be in the focus of attention. In the current study, we investigated what it means for information to reside in the focus of attention with respect to the impact of interference coming from the environment. Specifically, contradictory findings have been observed in the literature such that some studies have demonstrated that the focus of attention can protect specific information from external interference, whereas other studies have found that information in the focus of attention is rendered particularly vulnerable to external interference. Based on these studies in the literature, we investigated whether information in the focus of attention is protected from or particularly vulnerable to external interference. Our findings demonstrate that interference is neither protected from nor particularly vulnerable to external interference by default. However, in some very specific task situations, information that is assumed to be in the focus of attention appears to be more affected by external interference than other information in working memory, outside the focus of attention. Altogether, our results contribute to our understanding of the focus of attention as well as working memory more generally.

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Caro Hautekiet served as lead for visualization and writing–original draft. Marcel Niklaus served as lead for conceptualization, data curation, investigation, methodology, project administration, and software. Klaus Oberauer served as lead for funding acquisition, resources, and supervision and served in a supporting role for conceptualization, investigation, and methodology. Caro Hautekiet and Klaus Oberauer contributed equally to formal analysis. Marcel Niklaus and Klaus Oberauer contributed equally to writing–review and editing.

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Working memory is a system responsible for the selection, maintenance, and manipulation of information relevant for an ongoing task (e.g., Cowan, 1995; Oberauer, 2002). It has been found that representations in working memory are not all maintained in an equal state of accessibility. In particular, when attention is directed to specific information within working memory, this information is found to be in an increased accessible state, resulting in more accurate retrieval (e.g., Makovski et al., 2008; Rerko et al., 2014; Souza et al., 2016), faster reaction times (e.g., Griffin & Nobre, 2003; Hautekiet et al., 2024; Vergauwe & Langerock, 2017), and enhanced neural activity (e.g., LaRocque et al., 2013, 2016; Lepsien & Nobre, 2007; Lewis-Peacock et al., 2012). This heightened accessible state in working memory is often referred to as the focus of attention (e.g., Cowan, 1995; Garavan, 1998; McElree, 1998, 2006; Oberauer, 2002, 2009). Over the years, our understanding of the focus of attention has grown substantially. As such, some theorists have proposed that information in the focus of attention is stabilized and protected from interference (e.g., Cowan, 1999, 2001; Oberauer, 2002, 2009; Oberauer & Lin, 2017).

Many studies testing this conjecture made use of a retro-cue, which is a spatial cue that typically indicates the most relevant item for the upcoming memory test and is presented during the retention interval of a working memory task (Griffin & Nobre, 2003; Landman et al., 2003). When a retro-cue is used, the cued item has been found to be more accessible (e.g., Griffin & Nobre, 2003; Jeanneret et al., 2023; Souza et al., 2016; van Moorselaar et al., 2015; or see Souza & Oberauer, 2016 for a review) and protected from visual interference in comparison to the uncued items (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Makovski & Pertzov, 2015; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015). For example, in the study by van Moorselaar et al. (2015), participants were presented with three to-be-memorized line orientations. Next, a cue could be presented, which indicated the to-be-tested item with a 100% validity. After that, an interference display could be presented consisting of three pattern masks (i.e., six overlapping line orientations). At the end of the trial, one of these line orientations had to be reproduced. The cued item was found to be protected from interference by the mask, whereas the uncued items remained vulnerable to it. This demonstrates that the cued item, assumed to be in the focus of attention, is protected against visual interference, whereas the uncued items, outside the focus of attention, are not.

Contrary to this conclusion, another set of studies observed that a representation assumed to be residing in the focus of attention is particularly vulnerable to perceptual interference (e.g., Experiments 2–4, Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2014, 2016). For example, in the study by Hu et al. (2014), four colored shapes were presented in sequential order, a procedure which is thought to leave the last item in a prioritized state, which results in faster and more accurate responses for the last item compared to the earlier list items (i.e., last-presented benefit; e.g., McElree, 2006; McElree & Dosher, 1989; Nee & Jonides, 2008; Valentini et al., 2022; Vergauwe et al., 2016). Next, a visual distractor (or suffix) was presented. The suffix could be drawn from the same pool of items as the memory set (i.e., a plausible suffix) or it could be an unrelated abstract shape (i.e., implausible suffix). Then, participants were presented with either the shape or the color of one of the memory items, and they had to respond verbally with the corresponding other feature. For example, if one of the memory items was a yellow triangle and participants were presented with a triangle at the test display, they had to respond by saying "yellow."

Hu et al. (2014) observed that performance for the most recent item was increased relative to earlier list items (i.e., a last-presented benefit). The authors argued that this last-presented benefit arises because binding memory is fragile and is disrupted by the presentation of subsequent items. Whereas the earlier items suffer this type of interference from the subsequent items, the last item is free from this retroactive interference. Thus, when a suffix is presented after the last item, this is assumed to impact the most recent items more than the earlier items, which are already subjected to interference from the subsequent items (Hu et al., 2014; see also replication with continuous reproduction task; Hu et al., 2023). Indeed, in line with their assumptions, Hu and colleagues observed particular vulnerability for the last item of the sequentially presented list but also for the third list item (i.e., the second to last item). These findings led Hu et al. (2014) to postulate that a limited subset of memory items can be held in a privileged state in working memory (i.e., the focus of attention), which combines heightened accessibility with increased vulnerability. In line with these findings, several other studies demonstrated that prioritizing items in working memory by using reward values result in improved memory performance for the relatively highly-rewarded items but also puts them in a particularly vulnerable state in comparison to unprioritized items in working memory (e.g., Experiments 2–4, Allen & Ueno, 2018; Hitch et al., 2018; Experiments 2–4, Hu et al., 2014, 2016; see Baddeley et al., 2021 for recent overview; but see Experiment 1, Allen & Ueno, 2018; Hu et al., 2023). These results are in sharp contrast with the studies finding protection against visual interference for the item assumed to be in the focus of attention (see also Lorenc et al., 2021 for a recent review). Thus, it remains unclear whether focusing attention on specific information in working memory renders it more or less vulnerable to perceptual interference than not-focused information. Therefore, the current study aims to investigate whether information in the focus of attention is protected from or particularly vulnerable to visual interference.

The most prominent difference between the two groups of studies finding either protection or particular vulnerability is the way in which an item is being prioritized. The studies that observed particular vulnerability for the prioritized item made use of sequential presentation, whereby it is assumed that the last-presented item remains in the focus of attention in working memory (Experiment 1, Hu et al., 2014, 2016, 2023), or else, they presented participants with different reward values for the items in a memory set to motivate prioritizing the item with the highest reward (Experiments 2–4, Allen & Ueno, 2018; Hitch et al., 2018; Experiments 2–4, Hu et al., 2014, 2016; but see Experiment 1, Allen & Ueno, 2018; Hu et al., 2023; Vergauwe et al., 2024). By contrast, studies that observed protection for the prioritized item used a retro-cue to prioritize information in working

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memory (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Makovski & Pertzov, 2015; Rerko et al., 2014; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015).

Niklaus et al. (2019) demonstrated that the retro-cue benefit and the last-presented benefit are additive, and therefore, the last-presented benefit and the retro-cue benefit are unlikely to reflect the same mechanism. Because of this, Niklaus et al. (2019) argued that the retro-cue benefit reflects a goal-driven selection mechanism in working memory that is appropriately referred to as the focus of attention, whereas the last-presented item benefit might reflect an extreme point of a steep recency gradient on memory strength rather than the focus of attention (see also Donkin & Nosofsky, 2012). On the assumption that a retro-cued item is not in the same state as the last-presented item, we assume that retro-cued items are not subject to the same increased vulnerability as the last item, and hypothesize that instead, retro-cued items will be protected from visual interference. If this is true, this could mean that there are two different kinds of privileged states of information in working memory, one that protects the privileged information from visual interference, and one rendering the information more vulnerable. Alternatively, if the last-presented item and the retro-cued item are both represented in the focus of attention, we expect to observe the same result in terms of the susceptibility of this information to visual interference, regardless of the prioritization mode used.

Current Study

To investigate whether the susceptibility of an item to visual interference depends on the prioritization mode, we extended the suffix procedure of Hu et al. (2014) with a retro-cue (see Figure 1). Specifically, in Experiment 1, participants were sequentially shown four colored shapes. Next, in half the trials, a retro-cue was presented which indicated which item will be tested at the end of the trial. Crossed with the presence or absence of the retro-cue, on half the trials, a plausible suffix was presented (i.e., an item drawn from the same pool of items as the memory set). At the end of the trial, participants were presented with either the shape or the color of a randomly selected memory item, and they were asked to recall the corresponding feature.

Using this procedure, we wanted to examine if different ways of bringing an item into the focus of attention results in differences in terms of the distractor susceptibility of the item. Based on previous studies, we expected the most recent item(s) to be more vulnerable to visual interference than earlier items, whereas retro-cueing an item should protect the cued item from such interference. To test the former prediction, we used two separate analyses to accommodate two possible interpretations. The first one follows the typical assumption in the literature (going back to McElree & Dosher, 1989) that only the last-presented item of a sequentially presented list remains in the focus of attention. The second one is derived from the assumption that (a) "the recency effect observed by Allen et al. (2006) and others reflects cumulative retroactive interference on earlier items from subsequent items, the final item being entirely free from such interference" (Hu et al., 2014, p. 1666) and (b) "When a poststimulus suffix is presented it will generate additional retroactive interference, and this will be greater the more recent the item, resulting in a reduced recency effect" (Hu et al., 2014, p. 1666). One could interpret this as a linear increase in vulnerability to the suffix the more recently the item is presented in the list.

To accommodate both interpretations, we analyzed our results in two ways. First, we contrasted the last-presented item with the three earlier list items in a Bayesian logistic regression analysis. Using this analysis, we examined whether the last-presented item is particularly vulnerable to perceptual interference in comparison to earlier list items. Second, we ran another Bayesian logistic regression analysis in which the serial position of the items was coded linearly. Using this analysis, we examined whether the vulnerability of the item increases monotonically toward later list positions (i.e., whether the more recent items are particularly vulnerable to interference compared to the earlier items).

To foreshadow the results from our first experiment, we did not observe particular vulnerability for the most recent item(s) of a sequentially presented list. Instead, we observed that all items were equally vulnerable to the suffix, regardless of their serial position. When a 100% valid retro-cue was presented, we still observed that all items were equally vulnerable to the suffix, independent of their priority state. Thus, we did not find a particularly vulnerable state for the item in the focus of attention (contrary to Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2014, 2016), and we also did not observe protection for the item in the focus of attention (contrary to Barth & Schneider, 2018; Makovski & Jiang, 2007; Makovski & Pertzov, 2015; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015).

In four follow-up experiments, we attempted to get a better understanding of the susceptibility of information in working memory to visual interference. Specifically, we gradually adapted our paradigm to make the procedure more similar to the study by Hu et al. (2014; in our Experiment 2) or to make our procedure more similar to the studies that have observed protection for a cued item (in Experiments 3–5). As such, we varied the delay between the last item and the interfering suffix (Experiment 2), the number of suffixes (Experiment 3), the retrieval cue (Experiment 4), and the timing of the cue (Experiment 5). The data of all experiments are available on the Open Science Framework and can be found as the additional online materials (see https://osf.io/a8ufc/). None of the experiments were preregistered, and the study materials are available upon request.

Experiment 1

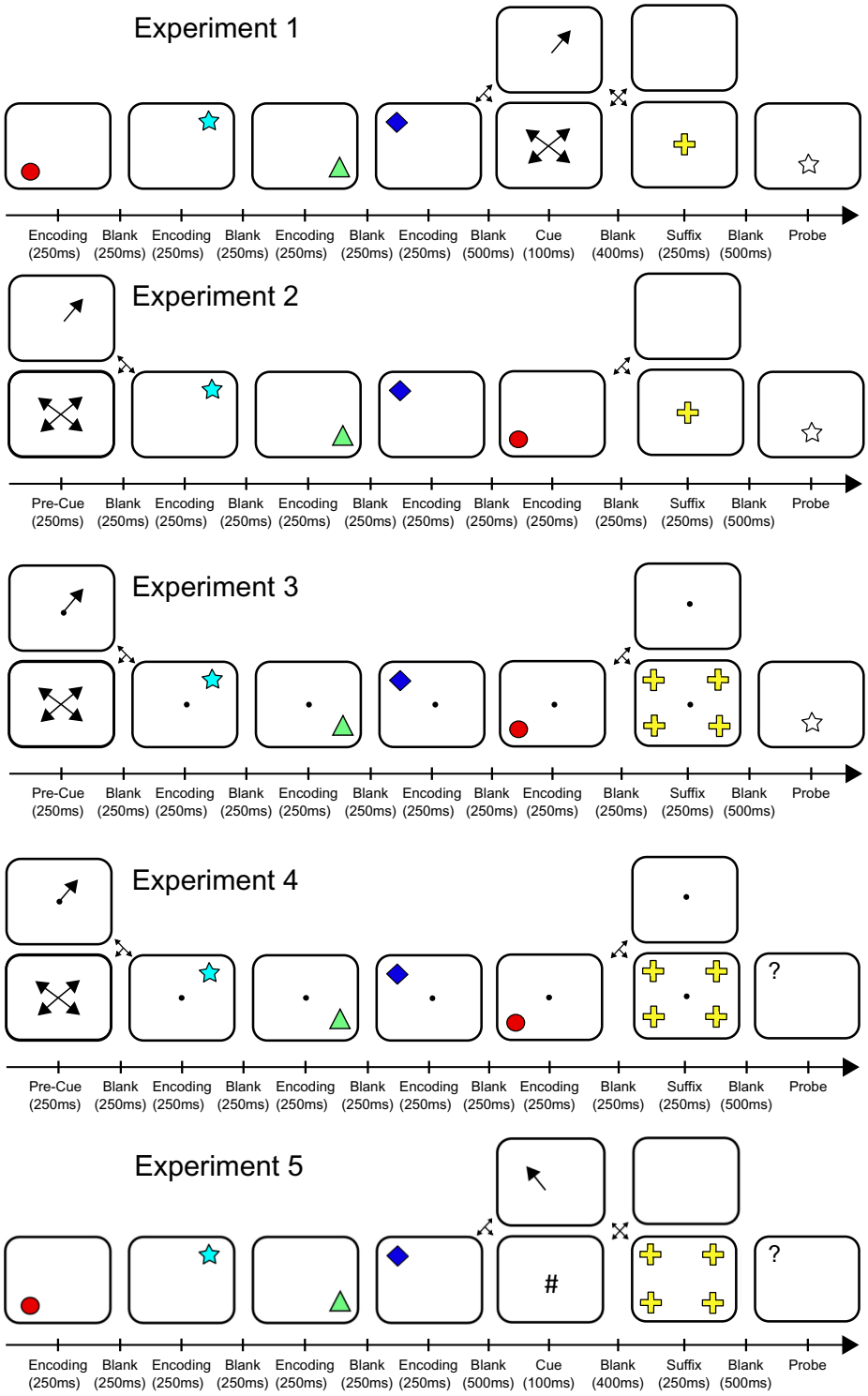
In our first experiment, we investigated whether different ways of bringing an item into the focus of attention can lead to differences in the item's susceptibility to visual interference. Specifically, we examined whether prioritization by means of being the most recent item(s) of a sequentially presented list leads to the item being particularly vulnerable, whereas prioritization by means of a valid retro-cue leads to the item being protected from visual interference in comparison to unprioritized items. To test this hypothesis, we used a paradigm very close to the one used in Experiment 1 by Hu et al. (2014) but including a valid retro-cue on half of the trials.

Method

Participants and Design

In total, 26 participants (17 females and nine males, $M_{age} = 25$) from the University of Zurich participant volunteer pool took part in this experiment in exchange for a payment. We determined the sample size for this and the subsequent experiments to be at least that of previous studies (Hu et al., 2014; van Moorselaar et al.,

Figure 1
Experimental Procedure Used in Experiments 1–5



Note. Before the sequence of events, a 50 ms fixation cross was presented, followed by the numbers "1–2–3–4" with a presentation time of 250 ms and an interstimulus interval of 250 ms. Participants were required to repeat this sequence aloud at a speed of two numbers per second until the onset of the test probe. See the online article for the color version of this figure.

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2015) that we used as starting points for designing the present experiments.[1] All participants read and signed an informed consent form before participation. This study, as well as the following, was carried out in agreement with the rules of the Ethics Committee of the Faculty of Arts and Sciences of the University of Zurich. Data collection of this experiment as well as the following was done in 2016–2017. The experiment realized a $4 \times 2 \times 2$ within-subject design with serial position (four levels; SP1, SP2, SP3, and SP4), cue type (two levels; neutral cue and valid cue), and suffix condition (two levels; no suffix and suffix) as within-subject variables.

Materials

The experiment was programmed and run in MATLAB using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). All memory items were selected from a pool of 64 color–shape combinations formed by crossing eight saturated colors (red [red, green, blue = 255,0,0], blue [0,0,255], yellow [255, 204,0], green [0,255,0], sky blue [0,255,255], purple [153,0,153], gray [153,153,153], and black [0,0,0]) with eight shapes (circle, diamond, triangle, cross, arrow, star, flag, and arch). Suffixes were selected from the same pool as the study items subject to the constraint that for each trial neither the color nor shape of the suffix was included among the four study items (i.e., a plausible suffix; see Hu et al., 2014). The probe was either a color blob (not matching any of the eight shapes) corresponding to the color of one of the study items or a black shape outline corresponding to the shape of one of the study items. Sets of four study items were constructed by a random selection from the pool of 64 items, with the constraint that no shape and no color was selected more than once per trial. These materials remained the same throughout the series of experiments presented here.

Procedure

Each trial began with the presentation of a fixation cross for 50 ms. Then, the numbers one through four were presented in the center of the screen with a presentation time of 250 ms and an interstimulus interval of 250 ms. Participants were required to repeat the sequence "1–2–3–4" aloud in (Swiss) German at a speed of two numbers per second until the onset of the test probe. This concurrent-articulation procedure served to discourage verbal encoding of the memory items. A 250-ms blank screen followed the end of the concurrent-articulation induction. From here on, the flow of events in Experiment 1 is depicted in the top row of Figure 1. On each trial, four color–shape items were presented one after another in the corners of an invisible square with a presentation time of 250 ms and an interstimulus interval of 250 ms. The spatial presentation order was random. The center of the invisible square was 1.5° of visual angle at a viewing distance of approximately 50 cm above the center of the screen, and the center-to-center distance between items was approximately 2.25°. After offset of the last item, and a 500-ms blank interval, we presented a cue for 100 ms. The cue was either neutral and consisted of four arrows pointing to each corner of the invisible square or it was a valid retro-cue, which indicated with certainty the spatial location of the item that was going to be probed.

After the offset of the cue, there was a 400-ms blank interval. Then, there either was a 750-ms blank screen in the no-suffix condition or a suffix was presented for 250 ms in the suffix condition, followed by a 500-ms blank screen. Suffixes were presented in the center of the screen. In all conditions, a 250-ms auditory beep was played 400 ms after the offset of the cue. This beep, coinciding with the onset of the suffix when there was one, was meant to help participants discriminate the suffix from the study items. Participants were informed, during the instructions, that they did not have to memorize the suffix. Finally, a test probe consisting of either a color blob or a shape outline appeared 1.5° below the center of the screen. When a color blob was presented, participants were required to recall the name of the shape associated with that color in the study sequence. When a shape outline was presented, they were required to recall the name of the color associated with that shape in the study sequence. We recorded participants' speech throughout the experiment.

The experiment consisted of a total of 288 trials divided into nine blocks. Each block resulted from a complete crossing of four probed serial positions, two dimensions (shape and color), two suffix conditions (suffix vs. no suffix), and two cue conditions (valid vs. neutral). Within each block, trials were presented in random order. Six practice trials were run before the experiment. The data of all experiments are available on the Open Science Framework and can be found as the additional online materials (see https://osf.io/a8ufc/). None of the experiments were preregistered, and the study materials are available upon request.

Analysis

In this experiment and the following, we performed two versions of a Bayesian logistic regression analysis using the brms package (Bürkner, 2017, 2018, 2021) in R (R Core Team, 2020). In the first version, we coded serial position as a contrast variable such that we contrasted the last serial position to the other three serial positions (SP1: −1/3, SP2: −1/3, SP3: −1/3, and SP4: 1). We will further refer to this analysis as the contrast analysis. In the second version, we coded serial position as a linear variable. We will further refer to this analysis as the linear analysis. For both analyses, we applied a Cauchy prior distribution with a location of 0 and a scale of 0.5 to the fixed effects. This choice of prior was based on simulations by Oberauer (2019), which show that Cauchy priors with scales between 0.3 and 0.7 on the logit scale translate into a broad prior on the probability scale that assigns substantial prior density to the entire range without being concentrated at the extremes. For the random effects, we used a Gamma prior distribution with a shape parameter of 1 and a rate parameter of 0.01. Markov-Chain Monte-Carlo chains were used to estimate the model parameters, and we fitted the models using eight chains and 29,000 iterations per chain after 1,000 warm-up adaptation steps. In each analysis, we started by testing whether there were any random effects (i.e., random slopes of the experimental procedure) for the interactions or main effects that should be included. Next, we start from the full model including all main effects and interactions as fixed effects as the initial best model. We test each interaction and main effect one by one by comparing the currently best model to a model in which that fixed effect (but not its random effect) is removed from the currently best model. Through this comparison, we establish the evidence in favor of or against including the effect under

[1] The sample sizes of the experiments included in this study vary between 24 and 35. We consider these sample sizes to be sufficient given that similar, or even smaller, sample sizes were sufficient to detect the protection/vulnerability effect in previous relevant studies in the literature at the time of data collection (see Hu et al., 2014, 2016; van Moorselaar et al., 2015).

investigation in the best model. Once we find evidence against including an effect in the best model, this effect is excluded from the best model for the remaining analysis. Following Jeffreys (1961), a Bayes factor (BF) of 10 or above is considered strong evidence, a BF between 3 and 10 is considered moderate evidence, and a BF lower than 3 is considered inconclusive evidence. Where applicable, we also used a Bayesian paired one-sided *t* test to examine whether the vulnerability score (accuracy no suffix–accuracy suffix) of the prioritized item(s) is larger than that of the unprioritized items (see Jeanneret et al., 2024; Vergauwe et al., 2024 for a similar procedure) or to compare the vulnerability scores between different serial positions.

Each analysis was first done on the trials in which a neutral cue had been presented. That is, a Bayesian logistic regression analysis of the number of correct neutral-cue trials was done with serial position (four levels: SP1, SP2, SP3, and SP4) and suffix (two levels: suffix and no suffix) as within-subject variables. After, the same Bayesian logistic regression analysis of the number of correct trials (including cue and neutral-cue trials) was done with serial position (four levels: SP1, SP2, SP3, and SP4), suffix (two levels: suffix and no suffix), and cue (two levels: valid cue, neutral cue) as within-subject variables.

Results

We excluded 1.5% of all trials because the participant's oral responses were not comprehensible or the participant responded with a feature of the not-probed dimension. We collapsed the data over dimension (color or shape recall) because it was not a variable of theoretical interest. Figure 2 depicts the mean proportion correct for each combination of cue type, suffix condition, and serial position.

Contrast Analysis

The results of the analysis on neutral-cue trials are presented in the upper section of Table 1. There was strong evidence in favor of a main effect of serial position. Memory performance was better for the last-presented item compared to the earlier items (i.e., items in Serial Positions 1, 2, and 3; see Figure 2). Furthermore, we observed strong evidence in favor of a main effect of suffix. Memory performance was generally worse when a suffix had been presented compared to when no suffix had been presented (see Figure 2). However, contrary to our expectations, we observed moderate evidence against an interaction between serial position and suffix. This suggests that the last-presented item is not particularly vulnerable to perceptual interference in comparison to earlier list items.

The lower section of Table 1 shows the result of the analysis of all trials. There was again very strong evidence for the main effects of serial position and suffix. Memory performance was better for the last-presented item compared to any of the other items. Memory performance was worse when a suffix was presented compared to when no suffix had been presented (see Figure 2). Furthermore, in line with the literature, there was very strong evidence for a main effect of cue. Memory performance was improved when a valid retro-cue had been presented compared to when a neutral cue had been presented (see Figure 2). However, contrary to previous findings in the literature, we observed very clear evidence against an interaction between cue and suffix, which suggests that the cued item was not protected from perceptual interference in comparison to the uncued items. In addition, there was no convincing evidence for any of the other two-way interactions nor the three-way interaction.

Linear Analysis

Table 2 (upper section) shows the results of the analysis with linear coding of serial position, focusing on the neutral-cue trials. We observed moderate and strong evidence for the main effects of serial position and suffix, respectively, and strong evidence against the interaction between serial position and suffix. This implies that the vulnerability of the items does not increase the later the items are presented in the list. Instead, all items appear to be equally affected by the presented interference.

The analysis of all trials (Table 2, lower section) showed strong evidence for the main effects of suffix and cue but strong evidence against the critical interaction between cue and suffix. This demonstrates that the cued item was not protected from perceptual interference in comparison to the uncued items. There was no convincing evidence for any of the other tested effects.

Discussion

The presentation of a suffix impaired memory performance regardless of the probe's serial position and regardless of whether the probed item had been cued or not. Thus, it seems that prioritized and unprioritized information are similarly affected by a suffix. We therefore found evidence against the claim that suffix especially impairs the prioritized item as suggested by Hu et al. (2014). We also found evidence against the opposite claim that the prioritized item is protected from visual interference (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015).

Thus, we did not replicate the findings by Hu et al. (2014; Experiment 1), although we used a highly similar paradigm. When we compare our experiment with the original study by Hu et al. (2014), the most noteworthy difference is the fact that the suffix was presented much later after the offset of the last-presented item in our study compared to Hu et al.'s study (1,000 ms vs. 250 ms, respectively). The reason for the longer delay in our task is the presentation of a cue in between the last item and the suffix. This longer delay can potentially explain the difference in results. Specifically, the focus of attention might have shifted away from the last-presented item by the time the suffix appears (e.g., Valentini et al., 2022; Vergauwe & Langerock, 2017). Our constant suffix costs across serial positions in the neutral-cue condition might therefore reflect a mixture of trials where the probed item was focused and impaired by the suffix, and trials where the probed item was not focused and therefore not or less affected by the suffix. In order to reduce the chance that the focus of attention shifts away from the last-presented item before the appearance of the suffix, we presented the suffix shortly after the offset of the last item in Experiment 2.

Experiment 2

As Experiment 1 did not replicate the results by Hu et al. (2014), we made our procedure even more similar to the original task of Hu and colleagues by shortening the delay between the presentation of the last item and the suffix (from 1,000 ms in Experiment 1 to 250 ms in Experiment 2). Because of this, we had to replace the retro-cue by a precue. A precue is very similar to the retro-cue, but

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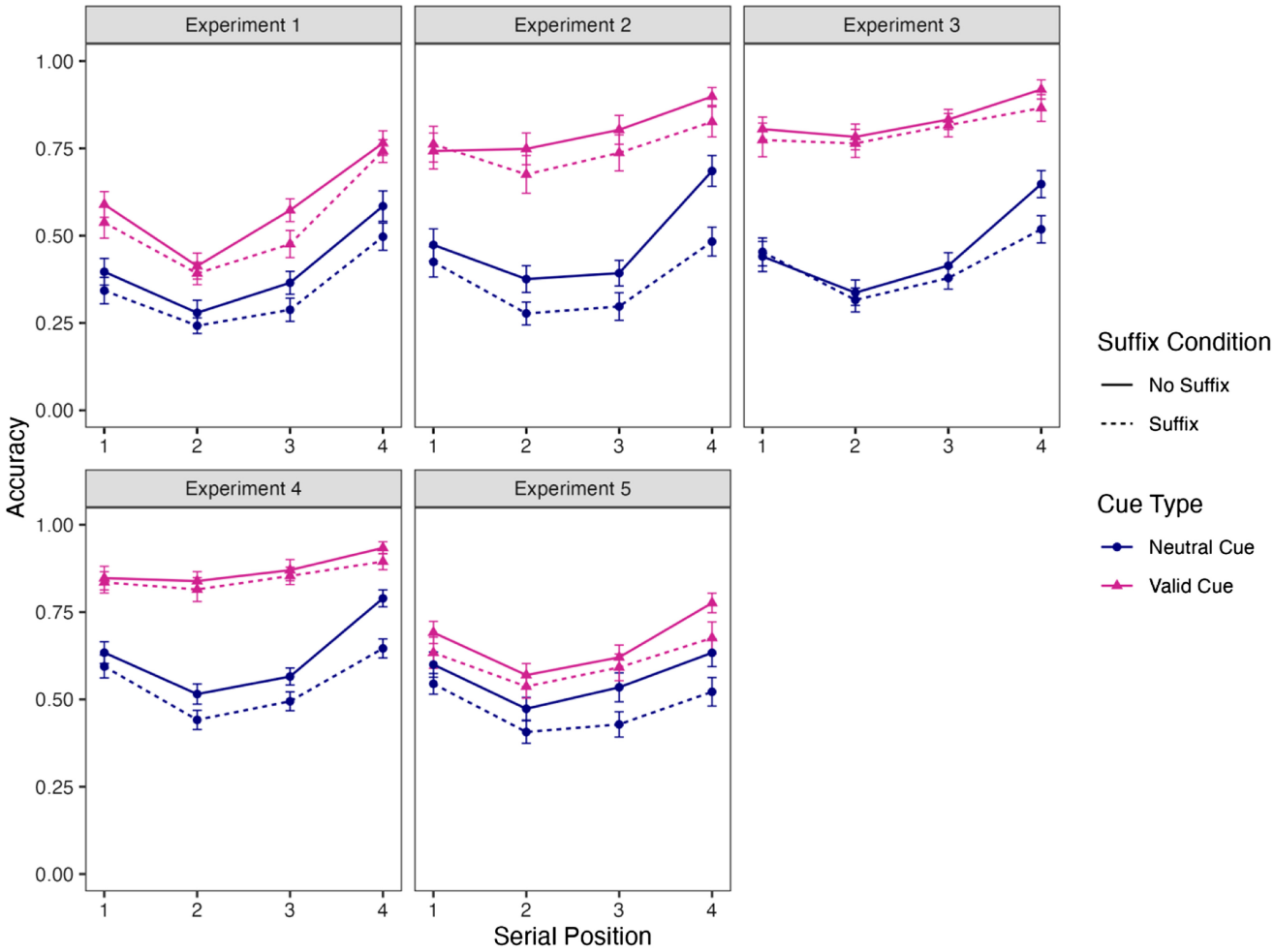
Figure 2

Mean Proportion Correct as a Function of Serial Position, Cue Type, and Suffix Condition for Experiments 1–5, Presented With Standard Error Bars (i.e., $M \pm 1$ SE)



Note. See the online article for the color version of this figure.

it is presented before encoding instead of during the retention interval (e.g., Griffin & Nobre, 2003; Janczyk & Reuss, 2016; Makovski & Jiang, 2007; Souza, 2016). Importantly, precues were not always valid to ensure that participants still had an incentive to encode all items in precued trials.

Method

Participants

In total, 25 participants (22 females, three males, $M_{age} = 24$) from the University of Zurich participant volunteer pool took part in this experiment in exchange for a payment. All participants read and signed an informed consent form before participation.

Procedure

The procedure of Experiment 2 is depicted in the second row of Figure 1. Following the end of the concurrent-articulation induction and a blank screen of 250 ms, a precue was presented for 250 ms, which indicated the spatial position of the item that is most likely to be probed (72.7% valid). After a 250-ms blank screen, the four color–shape items were presented sequentially as in Experiment 1. After the offset of the last stimulus, there was either a 1,000-ms blank interval (no-suffix condition) or a 250-ms blank screen, followed by a 250-ms suffix and a 500-ms blank screen (suffix condition). In all conditions, a 250-ms auditory beep (as in Experiment 1) was played 250 ms after the offset of the last item. In all other regards, Experiment 2 used the same design, materials, and procedure as Experiment 1. Moreover, apart from the presentation of a valid or neutral precue, this procedure is now the same as the plausible suffix condition of Experiment 1 by Hu et al. (2014).

The experiment consisted of a total of 266 trials divided into seven blocks. Each block resulted from a complete crossing of four probed serial positions, two dimensions of tested features, and two suffix conditions for neutral and validly cued probes. Therefore, there were as many neutral trials as validly precued trials. In addition, in each block, we added six invalidly cued probes, which result in a cue validity of 72.70% (16 of 22 cued trials for each block were

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Table 1

Bayes Factors (BF_{10}) From Bayesian Logistic Regression Analysis of Proportion Correct—Contrast Analysis

Tested effect	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5
Proportion correct, only neutral-cue probes					
SP	226.26	98.30	2.89×10^{16}	1.74×10^{4}	2.84
Suffix	15.17	367.58	0.99	1.70×10^{5}	1.21×10^{3}
SP × Suffix	0.14	5.72	3.65	543.21	0.21
Proportion correct, neutral and validly cued probes					
SP	1,588.85	459.80	1.69×10^{4}	1.53×10^{5}	157.71
Suffix	662.20	3,429.44	5.78	2.37×10^{5}	1,084.57
Cue	3.20×10^{9}	2.30×10^{5}	7.13×10^{6}	3.34×10^{10}	2.70×10^{5}
SP × Suffix	0.08	19.93	16.46	3,247.91	5.56
SP × Cue	1.48	0.15	0.11	0.07	7.30
Cue × Suffix	0.05	0.08	0.06	0.10	0.07
SP × Cue × Suffix	0.13	0.10	0.10	0.08	0.12

Note. Analysis is done with serial position coded as a contrast variable (SP1: −1/3, SP2: −1/3, SP3: −1/3, SP4: 1). The BF reflects evidence in favor of the tested effect (BF_{10}). When the BF reflects conclusive evidence (BF > 3) in favor of the tested effect, the text is presented in green; when the BF reflects conclusive evidence (BF > 3) against the tested effect, the text is presented in red; inconclusive results (BF < 3) are present in black. SP = serial position; BF = Bayes factor. See the online article for the color version of this table.

valid). Over the entire experiment, approximately the same number of invalid trials were shown for each combination of tested serial position, invalidly cued serial position, both suffix conditions, and both dimensions. Within each block, trials were presented in random order. Five practice trials were run before the experiment. Because the cue was not 100% valid, there were some trials on which one of the not-cued items was tested. However, as this was not a measure of interest, and to keep the analysis comparable to that of Experiment 1, these trials were excluded from the analysis.

Results

We excluded 0.81% of all trials because the participant's oral responses were incomprehensible or the participant responded with a feature of the nonprobed dimension. We again collapsed the data over dimension (color or shape). Additionally, for the trials in which a cue had been presented, we only included trials in which the cue validly indicated the to-be-tested item to keep the cue variable the same as in Experiment 1. This resulted in an exclusion of 15.74% of the trials.

Contrast Analysis

As reported in Table 1, the Bayesian logistic regression analysis for the neutral trials, with serial position coded as a contrast variable, resulted in very strong evidence in favor of the main effect of serial position and suffix. Memory performance for the last-presented item was improved in comparison to earlier items, and memory performance was worse with suffix than without (see Figure 2). There was moderate evidence for an interaction between serial position and suffix. As can be seen in Figure 2, the last-presented item was particularly affected by perceptual interference from the suffix. This was confirmed by a Bayesian paired one-sided *t* test which tested whether

Table 2

Bayes Factors (BF_{10}) From Bayesian Logistic Regression Analysis of Proportion Correct—Linear Analysis

Tested effect	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5
Proportion correct, only neutral-cue probes					
SP	7.31	1.33	5.05	3.79	0.11
Suffix	15.31	386.12	0.56	6.20×10^{4}	1,323.24
SP × Suffix	0.08	1.45	2.09	6.46	0.26
Proportion correct, neutral and validly cued probes					
SP	0.40	6.03	24.52	27.33	0.35
Suffix	689.32	3,340.73	4.07	8.44×10^{4}	683.83
Cue	2.38×10^{5}	2.23×10^{5}	6.67×10^{6}	3.48×10^{10}	2.36×10^{5}
SP × Suffix	0.52	23.12	1.74	11.95	0.46
SP × Cue	2.43	0.15	0.08	0.23	2.11
Cue × Suffix	0.07	0.07	0.06	0.10	0.07
SP × Cue × Suffix	0.03	0.05	0.07	0.04	0.03

Note. Analyses done with Serial Position coded as a linear variable. The BF reflects evidence in favor of the tested effect (BF_{10}). When the BF reflects conclusive evidence (BF > 3) in favor of the tested effect, the text is presented in green; when the BF reflects conclusive evidence (BF > 3) against the tested effect, the text is presented in red; inconclusive results (BF < 3) are present in black. SP = serial position; BF = Bayes factor. See the online article for the color version of this table.

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the vulnerability score (accuracy no suffix–accuracy suffix) was larger for the last-presented item compared to the other earlier presented items, although the evidence remained rather modest ($BF_{10} = 3.91$).

Next, we analyzed the full data set including both neutral and validly cued trials to investigate whether the cued item is protected from perceptual interference (see Table 1). In line with the results from Experiment 1, we again observed very clear evidence in favor of main effects of serial position, suffix, and cue. As can be seen in Figure 2, memory performance was improved for the cued items in comparison to the uncued items, was better for the last-presented item than the earlier items, and worse when a suffix had been presented compared to when no suffix had been presented. Furthermore, we observed strong evidence against the critical interaction between cue and suffix. Hence, the cued item was not protected from perceptual interference. In contrast, but in line with the results of the neutral trials, we did observe strong evidence in favor of the interaction between serial position and suffix. However, when we compared the vulnerability scores between the last-presented item and the earlier list items, the evidence of the Bayesian paired one-sided *t* test remained inconclusive ($BF_{10} = 2.22$).

Linear Analysis

The Bayesian logistic regression analysis for the neutral trials in which serial position was coded as a linear variable only demonstrated strong evidence in favor of the main effect of suffix (see Table 2). The evidence for the main effect of serial position and the interaction between serial position and suffix remained inconclusive (BFs < 1.50). This suggests that the vulnerability of the items does not increase the later they are presented in the list.

The analysis of the full data set (including both neutral and cue trials; Table 2) showed moderate to strong evidence for the main effects of serial position, suffix, and cue. However, we again observed moderate evidence against the interaction between serial position and cue, which suggests that the cued item is not protected from perceptual interference. There was strong evidence for the interaction between serial position and suffix. To further examine this interaction, we compared the vulnerability scores between the different serial positions to test whether each subsequent item is more vulnerable than the previous. As such, using a Bayesian paired one-sided *t* test, we observed inconclusive evidence for the vulnerability score of Serial Position 2 being larger than for Serial Position 1 ($BF_{10} = 2.38$), moderate evidence against the vulnerability score of Serial Position 3 being larger than for Serial Position 2 ($BF_{10} = 0.19$), and inconclusive evidence against the vulnerability score of Serial Position 4 being larger than for Serial Position 3 ($BF_{10} = 0.85$). To conclude, there is not much evidence that the susceptibility of the items increases the later the item is presented in the list. However, it does appear that the first item might be slightly less impacted by the presented interference in comparison to the more recent items (see Figure 2).

Discussion

Together, our first two experiments demonstrate that the item in the focus of attention is neither particularly vulnerable to nor protected from visual interference by default. Still, Experiment 2 demonstrates that the last-presented item can be somewhat more impacted by perceptual interference when the interference is presented shortly after the last item. However, the evidence for this particular vulnerability of the last-presented item was very modest and could only be observed when contrasting the last item with the earlier items. The results from our linear analysis demonstrated that there is no linear increase of the impact of the presented interference on the items toward the end of the list. Thus, there is some modest evidence for particular vulnerability of the last-presented item (as observed by Hu et al., 2014, 2016, 2023), but this vulnerability does not increase the more recently the item is presented in the list.

Furthermore, the results of Experiments 1 and 2 demonstrated very clear evidence against an interaction between cue and suffix, which implies that the cued item is not protected from perceptual interference in comparison to the uncued items. This finding deviates from several other studies by independent researchers who found evidence for protection of retro-cued items (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015). To further investigate these contrasting results, we compared our experiments with the most similar studies that have observed protection for a cued item in the past (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015). One of the most notable differences is the fact that studies finding protection for the cued item typically presented interfering stimuli spatially overlapping with the location in which memory items have been presented (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015), whereas the suffix was presented centrally in Experiments 1 and 2. Thus, it remains possible that the suffix presented in our task was not interfering enough for participants to strategically protect the prioritized item. Indeed, previous studies have shown that interference from visual stimuli is particularly strong when there is a spatial overlap with the memory items (e.g., Pinto et al., 2013). Thus, in an attempt to move closer toward the paradigms that have observed protection for a prioritized item in the past, we used the same procedure as in Experiment 2 but including a spatially overlapping interference display in Experiment 3 (i.e., the same suffix item in each of the locations of memory items).

Experiment 3

In this experiment, we investigated whether we could observe protection for the validly cued item when the suffix spatially overlaps with the memory items, as typically done in studies that have observed protection for the prioritized item in the past (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015). However, as we continued to use a similar paradigm as in Experiments 1 and 2, the current experiment also served as another examination of the distractor susceptibility of the most recent item(s) of a sequentially present list.

Method

Participants

In total, 25 participants (17 females, eight males, $M_{age} = 24$) from the University of Zurich participant volunteer pool took part in this experiment in exchange for a payment. All participants read and signed an informed consent form before participation.

Procedure

As depicted in the third row of Figure 1, we adapted the procedure in Experiment 3 only in one respect: Instead of a central suffix, we

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presented a suffix in each of the locations where the memory items had been presented. Additionally, a central fixation point was presented throughout the trial.[2] Within each trial, the shape–color combination of the suffix stimulus was the same for all four suffixes. The design and procedure are otherwise the same as in Experiment 2.

Results

We excluded 0.74% of all trials because the participant's oral responses were incomprehensible or the participant responded with a feature of the nonprobed dimension. We again collapsed the data over dimension. Like in Experiment 3, we excluded the trials in which one of the not-cued items was tested (i.e., invalid cue trials) as this was not of interest in the current study. This resulted in the exclusion of an additional 15.61% of the trials.

Contrast Analysis

The Bayesian logistic regression analysis for the neutral trials, with serial position coded as a contrast variable, resulted in very strong evidence for a main effect of serial position and inconclusive evidence against the main effect of suffix (see Table 1). As can be seen in Figure 2, memory performance was better for the last-presented item compared to the earlier presented items. Furthermore, we observed modest evidence for an interaction between serial position and suffix. To further explore this interaction, we calculated the vulnerability scores to examine whether the last-presented item is more vulnerable to the suffix than the not-last-presented items. The results of the Bayesian paired one-sided *t* test demonstrated inconclusive evidence in favor of this difference ($BF_{10} = 2.53$).

The same analysis on the full data set resulted in very clear evidence for the main effects of serial position and cue and moderate evidence for the main effect of suffix. As can be seen in Figure 2, memory performance was better for the last-presented item compared to the earlier items, when a cue was presented in comparison to when no cue was presented, and memory performance was worse with a suffix than without. Critically, there was strong evidence against the interaction between cue and suffix, again implying that the cued item was not protected from perceptual interference. Furthermore, we observed strong evidence in favor of the interaction between serial position and suffix. Bayesian paired one-sided *t* test on the vulnerability scores demonstrated that the last-presented item was impacted more strongly by the interference than the earlier list items ($BF_{10} = 6.05$).

Linear Analysis

Like in the previous experiments, we also analyzed the data with serial position coded as a linear variable. For the analysis of the neutral trials, this resulted in moderate evidence for the main effect of serial position (see Table 1). However, the evidence against the main effect of suffix, and for the interaction between serial position and suffix, remained inconclusive (BFs around 2).

In the analysis of the full data set, there was strong evidence in favor of a main effect of serial position and cue and moderate evidence for a main effect of suffix. Furthermore, there was inconclusive evidence for the interaction between serial position and suffix ($BF_{10} = 1.74$) and strong evidence against the other two-way interactions as well as the three-way interaction.

Discussion

In Experiment 3, we aimed to increase the strength of the suffix by making it spatially overlap with the memory display. In contrast with our aim, this weakened the evidence for the suffix effect compared to the previous experiments. Still, in line with our findings from Experiment 2, we did observe evidence for the interaction between serial position and suffix in the contrast analysis. However, when comparing the vulnerability scores of the last item and the earlier items, the vulnerability score was only substantially larger for the last item when taking into account the full data set (i.e., all trials regardless of whether a valid cue or a neutral cue was presented). These findings are in line with Experiment 2 such that some evidence can be observed for a particularly vulnerable state for the last-presented item when the suffix is presented shortly after the last item. Furthermore, in line with our previous experiments, we observed strong evidence against an interaction between cue and suffix. This again demonstrates that the cued item is not protected from interference.

Taken together, even though we attempted to make the paradigm more similar to the studies in the literature that have observed protection for the cued item, we again did not observe any interaction between interference and the cue. However, when comparing Experiment 3 with the relevant experiments in the literature, there is another difference that might be of importance. That is, in our experiment, the location of the memory items was not relevant for executing the task, and thus, participants did not have to memorize which item was presented in which location. Therefore, presenting the suffix in spatially overlapping locations might not have had the desired effect, as participants might not intentionally bind the memory items to the locations (see also Allen et al., 2015). In models such as SOB-CS ("serial-order-in-a-box-complex-span" model; Oberauer et al., 2012) or the network model of the phonological loop (Burgess & Hitch, 1999), retrieval is context-cue based. Stimuli are encoded by association to a context marker (such as serial position, spatial location, or an item feature), which can be used as a retrieval cue[3] to access the associated feature. In the studies that observed protection for the cued item, the spatial context was required to access the target feature (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015).

For example, in the study by van Moorselaar et al. (2015), three line orientations had to be remembered. At the end of the trial, the probe indicated one of the three memory locations. Participants were instructed to reproduce the line orientation that had been presented in that location. Thus, in this case, the spatial location of the memory item is important for the retrieval process. Among other things, a retrocue strengthens the binding between the cued item and its (spatial) context (e.g., Rerko & Oberauer, 2013; Souza & Oberauer, 2016). This strengthening of the content–context binding of the cued representation might also result in some protection for, in this case, the

[2] This fixation point was also present in Experiment 4 but not in any of the other experiments. Although it would have been more ideal if this had remained the same throughout the entire series of experiments, the inclusion of a fixation point was based on visual preference during programming and did not serve any additional purpose.

[3] Retrieval cues must not be confused with retro- and precues discussed so far. Retrieval cues, such as spatial location and serial position, are used to access and retrieve working memory representations which are associated to the retrieval cue.

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item–location binding from irrelevant, visual interference in the same location. To investigate this possibility, we used the same procedure as in Experiment 3 for Experiment 4, but we used spatial information as a recall cue during the memory test.

Experiment 4

In this fourth experiment, we wanted to examine whether we can observe protection for the cued item when the suffix is presented in spatially overlapping locations (as in Experiment 3), and spatial location is used as the retrieval cue. This procedure is similar to what has been used in previous studies that observed protection for a prioritized item in working memory (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015). Like in Experiment 3, the current experiment also served as another examination of the distractor susceptibility of the most recent item(s) of a sequentially present list because we used a similar paradigm as in the previous experiments.

Method

Participants and Design

In total, 35 participants (26 females, nine males, $M_{age} = 25$) from the University of Zurich participant volunteer pool took part in this experiment in exchange for a payment. All participants read and signed an informed consent form before participation.

Procedure

As depicted in the fourth row of Figure 1, we adapted the procedure in Experiment 4 with the following change. Instead of probing participants with a single feature of an object, we identified the tested object by a spatial probe, and participants were required to recall both features of that object. Therefore, the to-be-recalled probe was now indicated by a question mark ("?") in one of the locations of the previously presented memory items instead of presenting either the shape or the color (Experiments 1–3). As in the previous two experiments, the precue was 72.7% valid to encourage participants to encode all memory items. The design and the procedure were otherwise the same as in Experiment 3.

Results

We excluded 0.67% of all trials because the participant's oral responses were incomprehensible. Additionally, like in Experiments 2 and 3, we excluded trials in which one of the not-cued items was tested, as this was not of interest in the current study. This resulted in the exclusion of 15.8% of the trials. The dependent variable was the number of correctly recalled features per trial (i.e., 0, 1, or 2).

Contrast Analysis

As can be seen in Table 1, the Bayesian logistic regression for the neutral trials (with serial position coded as a contrast variable) resulted in very strong evidence for the main effects of serial position and suffix. Descriptively, memory performance was better for the last-presented item compared to the earlier list items, and memory performance was worse with a suffix than without. Additionally, we observed very strong evidence in favor of an interaction between serial position and suffix. One-sided *t* tests provided strong evidence for the vulnerability scores of the last-presented item being larger than that of earlier presented items ($BF_{10} = 70.19$).

The findings with the full data set were in line with Experiments 2 and 3 such that we observed very strong evidence for the main effects of serial position, cue, and suffix. As can be seen in Figure 2, memory performance was better for the last-presented item compared to the earlier list items, when a cue was presented compared to when no cue was presented, and worse with a suffix than without. As in the previous experiments, we observed strong evidence against the interaction between cue and suffix. Furthermore, we observed strong evidence in favor of the interaction between serial position and suffix. One-sided *t* test confirmed again that the vulnerability score of the last item was larger than the vulnerability score of the earlier list items ($BF_{10} = 55.54$). Hence, the last-presented item was indeed more vulnerable to perceptual interference than the earlier list items (in line with the results by Hu et al., 2014). This was the case regardless of whether an item was precued or not, as there was strong evidence against the three-way interaction.

Linear Analysis

The analysis of the neutral cue trials, with serial position as a linear predictor, showed modest evidence in favor of a main effect of serial position and strong evidence in favor of the main effect of suffix (see Table 2). Additionally, we observed moderate evidence for an interaction between serial position and suffix. Bayesian paired one-sided *t* tests comparing vulnerability scores of adjacent serial positions showed inconclusive evidence against the vulnerability score of Serial Position 2 being larger than the one of Serial Position 1 ($BF_{10} = 0.50$) and moderate evidence against the vulnerability score of Serial Position 3 being larger than the one of Serial Position 2 ($BF_{10} = 0.17$). However, the final *t* test resulted in strong evidence for the vulnerability score of Serial Position 4 being larger than the one of Serial Position 3 ($BF_{10} = 6.87$). Thus, in accordance with the contrast analysis, the last-presented item was particularly vulnerable to perceptual interference in comparison to all earlier list items.

The analysis of the full data set yielded strong evidence for the main effects of serial position, cue, and suffix. We again observed strong evidence against the interaction between cue and suffix, and hence, the cued item was not protected from interference in comparison to the uncued items. There was strong evidence for the interaction between serial position and suffix. A series of Bayesian paired one-sided *t* tests resulted in inconclusive evidence against the vulnerability score of Serial Position 2 being larger than the one of Serial Position 1 ($BF_{10} = 0.73$) and moderate evidence against the vulnerability score of Serial Position 3 being larger than the one of Serial Position 2 ($BF_{10} = 0.14$). The final *t* test again resulted in strong evidence for the vulnerability score of Serial Position 4 being larger than the one of Serial Position 3 ($BF_{10} = 9.52$). These findings demonstrate that the last-presented item of a sequentially presented list is impacted to a greater extent by perceptual interference in comparison to earlier list items.

Discussion

In this experiment, we observed that the last-presented item was clearly more affected by the suffix than the earlier list items. These results suggest that the last-presented item can indeed be

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particularly vulnerable to visual interference in comparison to the not-last-presented items in specific task situations (in line with Hu et al., 2014, Experiment 1; see also Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2016, 2023). These results are in line with our observations from Experiment 2 (neutral trials) and Experiment 3 (full data set) but contradict the findings from Experiment 1. The reason for this difference most likely lies in the fact that the suffix was presented shortly after the last item in Experiments 2–4, whereas there was a longer delay in Experiment 1 (in which the cue could be presented). Additionally, it is possible that the particular vulnerability of the last-presented item was most convincing in Experiment 4 because there was a spatial overlap between the memory items and the suffix, and spatial information was a relevant task component. Altogether, these findings suggest that the last-presented item is not particularly vulnerable to interference by default, but it can be impacted more strongly when (a) the interfering stimuli are presented shortly after the last item, (b) they spatially overlap with the memory items, and (c) the task requires spatial information as retrieval cue to the target information in working memory.

Furthermore, despite our efforts to optimize the paradigm, we again did not observe protection for a cued item, contrary to several findings in the literature (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Makovski & Pertzov, 2015; Rerko et al., 2014; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015). Like in Experiments 2 and 3, we used a precue to keep the delay between the presentation of the last item and the suffix the same. However, in the studies that found protection for a cued item, a retro-cue was used instead of a precue. Although these two are very similar (e.g., Griffin & Nobre, 2003), a precue is presented before encoding, whereas a retro-cue is presented after encoding. Thus, when a precue is presented, participants orient their spatial attention toward the stimuli in the cued location on screen, whereas participants orient their attention toward the cued item in working memory when a retro-cue is presented. Until now, we assumed that a precue and a retro-cue result in similar findings concerning the distractor susceptibility of information in the focus of attention, but there might be critical differences between these two that can influence the distractor susceptibility of an item (e.g., Janczyk & Reuss, 2016; Lepsien & Nobre, 2006; Tanoue et al., 2013). To investigate whether an item is protected from visual interference when a retro-cue is used, we reintroduced a retro-cue in our paradigm; otherwise keeping the features of Experiment 4. This experiment aligns more closely than Experiment 1 with studies that have observed protection for a cued item in the past (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015) as there is a spatial overlap between the suffixes and the memory items, as well as a location-based retrieval cue.

Experiment 5

In this final experiment, we reintroduced the retro-cue to investigate whether a retro-cued item is protected from visual interference as observed in the literature (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015). Like in Experiment 4, we presented multiple suffixes in the same locations as the memory items and used location as a retrieval cue. Following Experiments 3 and 4, we used this opportunity to examine whether the most recently presented item(s) is more susceptible to perceptual interference than earlier list items in this version of our paradigm.

Method

Participants and Design

In total, 24 participants (22 females, two males, $M_{age} = 22$) from the University of Zurich participant volunteer pool took part in this experiment in exchange for a payment. All participants read and signed an informed consent form before participation.

Procedure

Design and procedure were as in Experiment 1, except for the following differences. First, the neutral cue was now presented as a "#" instead of the four arrows pointing to the four locations.[4] Next, the suffix was presented in each of the memory locations, like in Experiments 3 and 4. Further, like in Experiment 4, the to-be-recalled probe was now indicated by a question mark ("?") in one of the locations of the previously presented memory items.

Results

We excluded 0.66% of all trials because the participant's oral responses were incomprehensible. The dependent variable was the number of correctly recalled features per trial (i.e., 0, 1, or 2).

Contrast Analysis

The analysis for the neutral trials with serial position coded as a contrast variable showed that there was inconclusive evidence for a main effect of serial position and strong evidence for a main effect of suffix (see Table 1). As presented in Figure 2, memory performance was worse when a suffix had been presented compared to when no suffix had been presented. However, like in Experiment 1, there was moderate evidence against an interaction between serial position and suffix. These findings suggest that all items were equally affected by the suffix, and thus, that the last-presented item was not particularly vulnerable to perceptual interference.

The results from the analysis of all trials showed very strong evidence for the main effects of serial position, cue, and suffix. As can be seen in Figure 2, memory performance was better for the last item compared to the earlier list items. Additionally, performance was improved when a valid cue had been presented compared to when a neutral cue had been presented, and performance was worse with a suffix than without. There was moderate evidence for the interaction between serial position and suffix. However, when we compare the vulnerability scores of the last-presented item and the earlier list items using a Bayesian paired one-sided *t* test, the evidence remained inconclusive ($BF_{10} = 2.31$) for the last item being particularly vulnerable in comparison to the earlier list items.

Furthermore, there was moderate evidence for the interaction between serial position and cue. As can be seen in Figure 2, it appears that the last-presented item might benefit slightly more from the presentation of a valid cue compared to the earlier list

[4] This was done to avoid any visual disturbance by the neutral cue as this was quickly followed by the suffix (presented in each of the four memory locations).

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items. However, when we compare this difference (accuracy for valid cue trails—accuracy for neutral cue trials) using a Bayesian paired one-sided t test, we observed inconclusive evidence ($BF_{10} = 1.69$) for this difference being larger for the last-presented item compared to the earlier list items. Next, and most critical to our research question, we observed strong evidence against the interaction between cue and suffix. Hence, the validly cued items were not protected from perceptual interference in comparison to the neutral cue condition.

Linear Analysis

With serial position coded as linear predictor, the analysis of neutral-cue trials yielded moderate evidence against a main effect of serial position, strong evidence for a main effect of suffix, and modest evidence against the interaction between serial position and suffix. These results again suggest that the items were equally affected by the suffix, and thus, that there is no linear increase in the vulnerability of the items the later they are presented in the list.

The same analysis for all trials together (valid cue trials and neutral-cue trials; see Table 2) showed that there was strong evidence for the main effect of suffix and cue, but, contrary to the previous experiments, we now observed inconclusive evidence against a main effect of serial position. Additionally, and most critically, we observed strong evidence against the interaction between cue and suffix. This once again confirms that the cued item was not protected from perceptual interference in comparison to the neutrally cued items.

Discussion

Our findings from Experiment 5 replicate the results from Experiment 1 such that we again observed that the last-presented item or most recently presented items of a sequentially presented list are not particularly vulnerable in comparison to earlier list items. This supports our assumption that to find such selective vulnerability of the last item, the suffix must follow shortly after the last item (as in Experiments 2–4).

In addition, we observed that the validly cued items were not protected in comparison to neutrally cued items. These results contradict earlier studies that demonstrated that a validly cued item is protected from interference (e.g., Makovski & Jiang, 2007; Schneider et al., 2017; van Moorselaar et al., 2015). We conclude that the lack of replication of those findings has nothing to do with whether items were precued or retro-cued.

General Discussion

The present study investigated the distractor susceptibility of an item assumed to be held in the focus of attention. Specifically, in the literature, opposing results have been obtained concerning the distractor susceptibility of information assumed to be in the focus of attention. On the one hand, it has been observed that such items are particularly vulnerable to perceptual interference (e.g., Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2014, 2016, 2023), whereas, on the other hand, several studies have observed that such items are protected from perceptual interference (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015; Zhang & Lewis-Peacock, 2023a). The former group of studies made use of a sequentially presented list and built on the assumption that the most recently presented item or items remained in the focus of attention (Experiment 1, Hu et al., 2014; see also Hu et al., 2016, 2023) or by assigning some memory items a higher reward value (Allen & Ueno, 2018; Hitch et al., 2018; Experiments 2–4, Hu et al., 2014, 2016, 2023). By contrast, the latter group of studies made use of a 100% valid retro-cue to bring one of the memory items into the focus of attention. In an attempt to resolve the debate concerning the distractor susceptibility of information in the focus of attention, the current study compared two of these prioritization modes within the same paradigm. We compared the distractor susceptibility of information of the last-presented item when memory items were presented sequentially and the cued item when a precue or a retro-cue was presented.

When memory representations are presented sequentially, it is often assumed that only the last-presented item will remain in the focus of attention (e.g., McElree, 1998, 2006; Nee & Jonides, 2011; Vergauwe & Langerock, 2017). However, Hu et al. (2014) predicted that "a to-be-ignored suffix would have its greatest effect on memory for the most recent items in a sequence" (p. 1675) and argued that there is a limited number of items—possibly more than one—that will benefit heightened accessibility for recall, and thus presumably reside in the focus of attention, but that will also be particularly susceptible to retroactive interference (see also Hitch et al., 2020, for a recent review). To accommodate different interpretations of these assumptions, we investigated (a) whether the last-presented item of a sequentially presented list is particularly vulnerable to perceptual interference in comparison to earlier list items, (b) whether the most recently presented items of a sequentially presented list are particularly vulnerable to perceptual interference in comparison to earlier list items, and (c) whether the validly cued items are protected from perceptual interference in comparison to the neutral-cue condition. Our findings are summarized in Table 3.

Our findings led to four main conclusions. First, the last-presented item of a sequentially presented list can be particularly vulnerable to perceptual interference in specific task situations, but this does not seem to be the case by default. Second, the vulnerability of sequentially presented memory items does not increase gradually the more recently the items are presented in the list.[5] Third, a valid cue does not protect the cued information from perceptual interference. Fourth, overall, it seems that, in most task situations, memory representations are equally vulnerable to perceptual interference, regardless of their priority state or the used prioritization mode. In the next section, we will discuss what these findings mean for our understanding of the focus of attention in working memory.

Distractor Susceptibility in the Focus of Attention: Protected or Particularly Vulnerable?

Hu et al. (2014) consistently demonstrated that the increased performance for the prioritized item(s) comes with an increased susceptibility to visual interference (for similar findings, see

[5] One could argue that the linear analyses used to investigate increased vulnerability for more recently presented items might not be ideal because of the potential presence of a primacy effect that could counter the linearity of the results. However, we mostly observed evidence against ($BF_{10} > 3$) the presence of a primacy effect in our experiments, except for Experiment 5 (see the online supplemental materials for the results).

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Table 3
Overview of Findings From Experiments 1–5

Trial	EXP 1	EXP 2	EXP 3	EXP 4	EXP 5
Particular vulnerability for last-presented item					
Neutral trials	✗	(✓)	✗	✓	✗
All trials	✗	✗	✓	✓	✗
Increased vulnerability for more recently presented items					
Neutral trials	✗	✗	✗	✗	✗
All trials	✗	✗	✗	✗	✗
Protection for validly cued items					
All trials	✗	✗	✗	✗	✗

Note. A checkmark "✓" indicates that there was clear evidence in favor of the assumption, a checkmark between brackets means that there was evidence for the assumption, but it remained modest, and a cross "✗" means our findings do not support the assumption. "All trials" refers to analyses including trials with a valid and a neutral cue. "Neutral trials" refers to analyses on the subset of trials with a neutral cue. EXP = experiment.

Experiments 2–4; Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2016). In agreement with this, we observed that the last-presented item was particularly vulnerable to visual interference in Experiments 2–4. However, it should be noted that the evidence in Experiment 2 remained modest and was only observed for the neutral-cue trials, and that the evidence in Experiment 3 was only observed when analyzing all trials together. In Experiments 1 and 5, the evidence was very clearly against increased vulnerability for the last-presented item(s). Furthermore, our paradigm also allowed for an analysis of the type of errors that were made (see the online supplemental materials for the results of this analysis). This analysis demonstrated that the suffix stimuli were more likely to intrude than any of the other, not-included stimuli. However, these intrusions were not more prevalent for the last presented item.

Altogether, our findings suggest that the evidence for particular vulnerability for the last-presented item remains modest and can only be observed in very specific task situations. The task parameters that most likely play a role in observing particular vulnerability for the last-presented item are (a) the time between the last-presented item and the interference display and (b) the strength of the interference items. Specifically, the only occasions where we observed evidence for particular vulnerability of the last-presented item was when the interference display was presented very shortly after the last presented item (i.e., 250 ms following the offset of the last item; in Experiments 2–4). Additionally, the most convincing evidence for particular vulnerability of the last-presented item was observed when the interference items were presented in the same spatial locations as the memory items and when location was a task-relevant component (in Experiment 4), which potentially made the suffix interference stronger than when it was presented centrally or when locations were task irrelevant. These findings suggest that there might be strict boundary conditions (related to the timing and spatial location of the suffix) for observing a particular vulnerability for the last-presented item. Taken together, our findings demonstrate that (a) the last-presented item of a sequentially presented list is not particularly vulnerable by default but said item can become particularly vulnerable in specific task situations (in line with the observations by Hu et al., 2014, 2016, 2023) and (b) there is no gradual increase in the vulnerability of sequentially presented memory items, and thus, the more recent items are not particularly vulnerable to perceptual interference.

Furthermore, we consistently found that a validly cued item was not protected from visual interference contrary to different findings in the literature (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Rerko et al., 2014; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015). Whereas these studies made use of a 100% valid retro-cue and consistently observed protection for the cued item, we used a (highly) valid precue or a 100% valid retro-cue and consistently observed that memory representations have a similar level of vulnerability regardless of their priority state in working memory. Across Experiments 3 and 4, we changed several task parameters that differed between our paradigm and the previous studies that have observed protection for a validly cued item in working memory and removed all those differences that we think could explain the discrepant results in Experiment 5. Still, we did not observe any change in the susceptibility of the validly cued item toward visual interference in comparison to the neutral-cue condition. Thus, our results suggest that a prioritized item, assumed to be in the focus of attention, is equally vulnerable to visual interference as other items in working memory, outside the focus of attention. These findings contradict models of working memory that have proposed that information in the focus of attention is protected from perceptual interference (e.g., Cowan, 1999; Oberauer & Lin, 2017). They are also difficult to reconcile with theories assuming that items in the focus of attention are in general particularly vulnerable to interference in comparison to other information outside the focus of attention (e.g., Baddeley et al., 2021; Hitch et al., 2020).

Still, this is not the first time that results such as ours have been obtained. There are at least six studies in the literature that have observed a similar pattern (Experiment 1, Allen & Ueno, 2018; Hautekiet et al., 2024; Hu et al., 2023; Jeanneret et al., 2024; Vergauwe et al., 2024; Zhang & Lewis-Peacock, 2023b). For example, Allen and Ueno (2018) did not observe particular vulnerability for the high-reward item when there was only one high-reward item in their Experiment 1. Even more so, the high-reward item (assumed to be in the focus of attention) was equally vulnerable to the suffix interference as the low-reward items (assumed to be outside the focus of attention). Their task was very similar to the paradigm used in the current set of experiments, except that the memory items were presented simultaneously. To prioritize information in working memory, Allen and Ueno presented participants with a reward pattern at the start of each trial. This reward pattern indicated to the participants which reward (high vs. low) was associated with each of the four upcoming memory items. When there was one high-reward and three low-reward items, all items were equally vulnerable to perceptual interference regardless of their reward value. As soon as multiple items were assigned a high reward, the high-reward items became more vulnerable to visual interference than the low-reward items (Experiments 2–4, Allen & Ueno, 2018). In a similar study, Hu et al. (2023) compared the susceptibility of memory information when the first item of a sequentially presented list is to-be-prioritized compared to when no prioritization instructions are provided. The results showed that memory representations were equally vulnerable to the presented suffix regardless of the prioritization. Our findings are similar to the results by Allen and Ueno (2018, Experiment 1) and Hu et al. (2023) in that we also observed that an item assumed to be in the focus of attention (i.e., the validly cued item) is equally vulnerable to visual interference as any of the other items in working memory, outside the focus of attention.

Similarly, a recent study by Vergauwe et al. (2024) observed that memory representations are equally vulnerable to visual interference

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regardless of how the memory items are presented (sequential vs. simultaneous), when the priority signal is presented (before, during, or after memory encoding), and what the priority status of the item was (prioritized vs. unprioritized). In this study, the first experiment consisted of a conceptual replication of Experiment 1 by Hu et al. (2014) in which three items were presented sequentially, and the delay between the last item and the suffix was varied (250–700 ms). The results showed that the last-presented item was not particularly vulnerable to the presented interference. Instead, all items appeared to be equally vulnerable regardless of their assumed priority status. In a second experiment, Vergauwe and colleagues did a conceptual replication of Experiment 1 by Allen and Ueno (2018) in which four memory items were presented simultaneously and a priority signal was presented before, during, or after encoding. This priority signal indicated to the participants which item would result in a high reward when tested and responded to correctly, whereas the other items would result in a low reward. The memory items were equally vulnerable to the presented suffix, regardless of the reward value associated with the item (i.e., the priority status) or when the priority signal had been presented (see also Jeanneret et al., 2024, for similar findings using verbal materials). Our results align with the findings by Vergauwe et al. (2024) such that we also did not observe consistent evidence pointing toward a particularly vulnerable state for the item assumed to be in the focus of attention. Additionally, like Vergauwe et al.'s findings, our results indicate that items in working memory are, in most task situations, equally vulnerable to visual interference regardless of their assumed priority state.

The critical difference between the studies that have observed particular vulnerability, equal vulnerability, or protection for the prioritized item could be the validity of attentional direction (see Allen et al., 2025). Specifically, while the studies finding particular vulnerability have mostly relied on uninformative prioritization (i.e., reward values or the last-presented item), studies finding protection have mostly relied on informative prioritization (i.e., 100% valid retro-cues). In the latter, participants know which item will be tested, whereas in the former, all items still have an equal chance of being tested. This difference in validity could result in differences in the susceptibility of the prioritized item toward perceptual interference. This hypothesis has been extensively investigated by Hautekiet et al. (2024) in which prioritization through different levels of retro-cue validity and reward values was compared within the same paradigm to examine the differences in distractor susceptibility. However, throughout 10 experiments, the authors did not observe any convincing evidence for a detrimental impact of perceptual interference on memory performance, regardless of the priority state of the items (prioritized vs. unprioritized), the used prioritization mode (retro-cue vs. reward), or the validity of the cues. A similar approach was used in Jeanneret et al. (2024) and Zhang and Lewis-Peacock (2023b) and, in both studies, similar results were obtained. While these studies did not resolve the difference in validity hypothesis, they demonstrate that the more prominent question might be when and why working memory is affected by perceptual interference, before continuing the investigation as to what it means for information to reside in the focus of attention with respect to the impact of perceptual interference.

Taken together, based on our results and the recent findings in the literature, it appears that when memory is affected by perceptual interference, the detrimental impact of the suffix generally does not differ for information inside the focus of attention compared to information outside the focus of attention. Thus, information in the focus of attention is neither protected from nor particularly vulnerable to perceptual interference by default. Instead, information in the focus of attention can become particularly vulnerable (or protected) depending on the specific task situations. Future studies should further investigate why information is impacted differently by perceptual interference in specific task situations.

Conclusion

Over the course of five experiments, we observed that (a) the last presented item, which is assumed to be in the focus of attention, is not particularly vulnerable to visual interference by default; (b) the most recently presented items of a sequentially presented list are not particularly vulnerable to visual interference; and (c) a validly cued item, assumed to be in the focus of attention, is not protected from visual interference. With that, we challenge the generality of the proposition that items in the focus of attention are either particularly vulnerable (e.g., Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2014, 2016) or protected from (e.g., Barth & Schneider, 2018; Makovski & Jiang, 2007; Schneider et al., 2017; Souza et al., 2016; van Moorselaar et al., 2015) visual interference in comparison to items outside the focus of attention. On the contrary, our results suggest that information in working memory is, under many circumstances, equally vulnerable to visual interference, regardless of its priority state and the used prioritization form.

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