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Attentional effects on orientation judgements are dependent on memory consolidation processes

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Are the effects of memory and attention on perception synergistic, antagonistic, or independent? Tested separately, memory and attention have been shown to affect the accuracy of orientation judgements. When multiple stimuli are presented sequentially versus simultaneously, error variance is reduced. When a target is validly cued, precision is increased. What if they are manipulated together? We combined memory and attention manipulations in an orientation judgement task to answer this question. Two circular gratings were presented sequentially or simultaneously. On some trials a brief luminance cue preceded the stimuli. Participants were cued to report the orientation of one of the two gratings by rotating a response grating. We replicated the finding that error variance is reduced on sequential trials. Critically, we found interacting effects of memory and attention. Valid cueing reduced the median, absolute error only when two stimuli appeared together and improved it to the level of performance on uncued sequential trials, whereas invalid cueing always increased error. This effect was not mediated by cue predictiveness; however, predictive cues reduced the standard deviation of the error distribution, whereas nonpredictive cues reduced "guessing". Our results suggest that, when the demand on memory is greater than a single stimulus, attention is a bottom-up process that prioritizes stimuli for consolidation. Thus attention and memory are synergistic.

Keywords: Spatial attention; Memory; Visual working memory; Visual short-term memory; Visual perception.

The effects of memory and spatial attention on visual perception are typically studied as independent. Most articles focus on one or the other process and use distinct experimental and analytic procedures. In a typical memory task, stimuli are transiently presented, and participants have to recall, recollect, or recognize items after a delay (Baddeley, Eysenck, & Anderson, 2009). Spatial attention tasks usually have participants detect or discriminate items that are present until report (Benjafield, Smilek, & Kingstone, 2010).

From these distinct, parallel approaches we have learned important facts about memory and spatial attention. For example, we know that it takes more time to consolidate multiple stimuli when they are presented simultaneously than when they

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are presented sequentially (Jolicoeur & Dell'Acqua, 1998) and that attentional cues reduce response times (Posner, 1980; Posner, Snyder, & Davidson, 1980), improve accuracy (Posner, 1980), increase precision (Anderson & Druker, 2013; Prinzmetal, Amiri, Allen, & Edwards, 1998), and reduce noise (Baldassi & Burr, 2000; Dosher & Lu, 2000; Palmer, 1994; Shiu & Pashler, 1995).

While memory and spatial attention are often studied separately, they may still rely on common components or mechanisms. In this paper we employ a task that allows for a memory manipulation, a spatial attention manipulation, or both. By comparing and contrasting the results of these manipulations, we can begin to address the independence or dependence of memory and spatial attention processes. Since our task will manipulate memory through the use of sequential and simultaneous presentation of items, and attention through the use of spatial cueing, we provide a brief overview of these manipulations as an introduction to our experiments.

Exogenous spatial cueing and response accuracy

A common procedure for manipulating spatial attention is to use an exogenous spatial cue. The intuition is that such abrupt onset events involuntarily direct the attention of a participant to the cued spatial location. Posner's (1980) seminal work using central (endogenous) and peripheral (exogenous) cues to capture attention demonstrated that peripheral cues in the form of dots or bars that appear in potential target locations improved response time and accuracy when they appeared in the same location as the target, and hurt response time and accuracy when they appeared elsewhere. These early results have been replicated many times (reviewed in Carrasco, 2011).

Mechanisms of performance improvement

Several theories have been put forward to explain how exogenous, spatial cues improve the performance on tasks involving targets in the attended locations. One theory suggests that the target's signal is enhanced via an increase in spatial resolution (reviewed in Anton-Erxleben & Carrasco, 2013). Much of the work on spatial resolution, however, does not involve making judgements about stimuli held in memory or making judgements about only one of multiple stimuli.

Another possibility is that spatial attention helps to select the target for processing by suppressing distractor stimuli and/or reducing uncertainty. Shiu and Pashler (1994) presented participants with single digits that were precued with a valid, invalid, or neutral cue. Following the target, one or multiple masks appeared in target and nontarget locations. The authors found that participants made the same amount of errors on valid trials when there were multiple and single masks, but made significantly more errors on invalid trials only when there were multiple masks. This result suggests that spatial precueing improves accuracy by suppressing distractors. Solomon, Nilli, and Morgan (1997) had participants indicate whether a target was higher or lower in contrast to three distractors of equal contrast and found that performance was improved when the target location was validly cued compared to uncued. The authors concluded that their result was best explained by uncertainty reduction of the location of the target in the array.

Another issue for attentional experiments is the nature of the cue. Cues may have effects simply due to their physical salience or because they communicate information about a possible target. There is increasing evidence that spatial probabilities are one route by which cues influence perceptual judgements (Enns & Brodeur, 1989; Eriksen & Yeh, 1985; Johnson & Yantis, 1995; Jonides, 1980). Recently, Droll, Abbey, and Eckstein (2009) found that the cueing effect increased as the information available (via feedback) to learn the cue predictiveness also increased. Druker and Anderson (2010) showed that people can learn spatial probabilities in the absence of such feedback, and that performance is improved for targets in probable locations. Furthermore, Jiang, Swallow, Rosenbaum, and Herzig (2013) demonstrated using a visual search task that after a few dozen trials participants became biased towards the location where the target was most probable to appear, and that this bias persisted even when the context changed.

Visual short-term memory

Experiments that assess attentional effects with transient stimuli intermingle the effects of memory and attention making it difficult to apportion between them responsibility for any effects on response accuracy. Recent studies by Liu and Becker (2013) and Anderson and Druker (2013) indicated a way forward in that they essentially used the same procedures to examine memory and attentional processes. Liu and Becker (2013) investigated whether the increased amount of time taken to make a perceptual report of one of multiple stimuli in memory was the result of a serial bottle-neck or a resource limitation. Using a procedure adapted from work by Wilken and Ma (2004), their participants were presented with two types of trials (sequential and simultaneous) and were required to make an orientation judgement from memory. Liu and Becker fitted a mixture model, originally developed by Zhang and Luck (2008), composed of a von Mises function (akin to a normal distribution on the circle) and a uniform distribution to the distribution of errors. From the parameters of this mixture they estimated parameters for precision (standard deviation of the von Mises function), bias (mean of the von Mises function), and guessing probability (the mixing proportion for the uniform distribution). Liu and Becker found that accuracy was better on sequential trials than on simultaneous trials, and that the accuracy improvement was associated with a decrease in the guessing probability without changes in the precision or bias parameters. Liu and Becker concluded that there was less frequent guessing on sequential trials and that this supported the hypothesis that consolidation of orientation information is serial. In contrast, using a similar task but different analysis methods, Anderson and Druker (2013) reported that the improved accuracy for orientation judgments with exogenous cueing was due to an improvement in precision. As the two tasks used different manipulations with otherwise very similar procedures it became possible to envision combining the two tasks together to look for memory and attentional effects in a single task.

Attention and memory together

Attention experiments that mimic memory procedures and ask participants for their responses after stimuli have disappeared are only now beginning to emerge. Sergent et al. (2013) found that orientation judgements were improved when spatial attention was oriented to the location previously occupied by a Gabor, demonstrating that postcued attention can serve to revive a stimulus that might otherwise have been lost. Murray, Nobre, Clark, Cravo, and Stokes (2013) demonstrated this effect using multiple stimuli. Participants were required to report the orientation of one of four arrows, and the proportion of responses correct was highest when the location of the target arrow was postcued before participants were prompted to respond.

A recent study using precues by Pack, Klein, and Carney (2014) provided evidence that signal enhancement and spatial uncertainty reduction were insufficient to explain cueing effects of transient stimuli (see also Cameron, Tai, & Carrasco, 2002). Following a nonpredictive cue (a green arc; 14.3% valid in their Experiment 1 and 50% valid in their Experiment 2), participants were presented with an array of one number (the target) and six letters (the distractors), equally spaced and arranged in a circle around centre. The contrast of the stimuli varied from 19% to 100%. The task was to first localize the target by indicating its location and then identify the target by indicating what number it was. In both experiments, participants were more accurate, and to the same degree, for localizing the target and identifying the target on validly cued trials compared to invalidly cued trials. There was no increase in the size of the cueing effects for either the magnitude of the accuracy difference or the slope of accuracy by contrast function. If signal enhancement and uncertainty reduction could explain these results you would expect increases in the size of the cueing effects, whereas none were observed.

Present research

The purpose of the present research was to investigate the effects of spatial attention and memory on performance when memory and spatial attention were manipulated in the same task. We used an exogenous, spatial precue to orient attention and sequential or simultaneous presentation of stimuli to manipulate memory. The spatial cues always appeared after an initial interval of fixation at the start of a trial in the first three experiments, and the cues were 100% valid in Experiment 1, 80% valid in Experiment 2, and 50% valid in Experiment 3. In the final two experiments there were two types of sequential trials: one where the cue appeared before the onset of the first stimulus and one where the cue appeared before the onset of the second stimulus. The cues were 80% valid in Experiment 4 and 50% valid in Experiment 5. Consequently, we were able to evaluate whether there are differences in the attentional affects for nonpredictive and predictive spatial cues, as well as whether these effects interact with a manipulation of memory. As cued trials were intermixed with an equal number of uncued trials, we could also evaluate memory effects using the sequential–simultaneous comparison employed by Liu and Becker (2013). The present study, therefore, serves several functions. First, it is a replication of Liu's and Becker's recent work on memory consolidation. Second, it presents new results relevant for the mechanisms by which attentional cues affect perceptual judgements of a continuous response metric, orientation. Thirdly, since memory and attention are manipulated together in the same task, we can evaluate their interaction or independence.

GENERAL METHOD

The procedures that were the same across all experiments are described here. Any differences or additions to individual experiments are described in the method section for that particular experiment.

Participants

The sample size for all experiments was chosen based on previous research using a similar protocol (Anderson & Druker, 2013). All participants reported normal or corrected-to-normal visual acuity. The experiments were approved by the Office of Research Ethics at the University of Waterloo, and all participants signed informed consent prior to participation.

Stimuli, design, and procedure

The experiments were programmed in Python using the PsychoPy library (Pierce, 2007). Stimuli were displayed on a 33×26.5-cm CRT monitor with a screen resolution of 1024×768 pixels and a refresh rate of 84 Hz. Participants were seated at a viewing distance of 60 cm. All stimuli were presented on a grey background with a luminance of 39.3 cd m^{-2}.

The stimuli and procedure were designed to be a close replication of the stimuli and procedure used by Liu and Becker (2013). The addition of a spatial precue is new in the experiments reported here. The stimuli consisted of circular sinusoidal gratings (size: 1.5°; spatial frequency: 2 cycles/degree, contrast: 0.7), circular noise masks (size: 1.8°; 200 white, one-pixel dots), and a spatial precue of four black dots (size: 0.3°). During the practice trials participants heard a high-pitch tone (http://www.freesound.org/people/Bertrof/sounds/131660/) if they were within $\pm 10°$ of the correct orientation and a low-pitch tone (http://www.freesound.org/people/Bertrof/sounds/131657/) if they were outside of that range. No auditory feedback was provided during the experimental trials.

Participants made orientation judgements from memory in three general trial types: set size one (practice trials only), sequential, and simultaneous. The trial structure and timing for each trial type is shown in Figure 1. In the set size one condition a single grating was presented in one of four possible locations, the corners of an imaginary square (size:

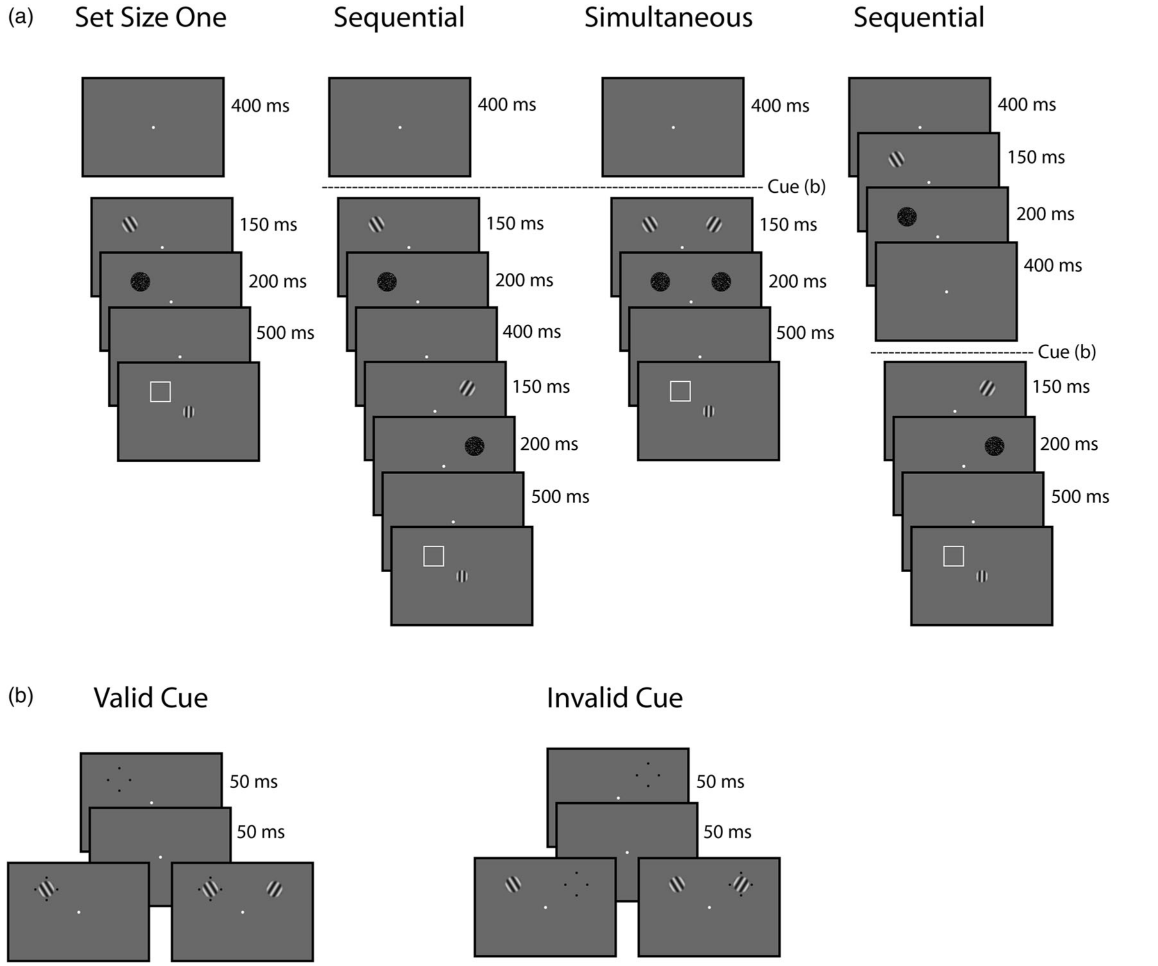

Figure 1. *General procedure. (a) The set size one condition only appeared in the practice trials, and for both the practice and the experiment the conditions were blocked. One or two circular gratings, which were backwards masked (black circles with white pixel dot noise), were displayed. In the sequential conditions the gratings were presented one after the other, and in the simultaneous condition they were presented at the same time. When participants were prompted for a response, a white square (response probe) appeared in a location previously occupied by a grating to indicate which grating should be recalled. Participants were required to rotate a central response grating to match the angle of the indicated grating. (b) On half of the experimental trials a spatial precue, consisting of four black dots, appeared before the presentation of the first stimulus in one sequential block type (all experiments) and before the second stimulus in another sequential block type (Experiment 4 and Experiment 5). In the simultaneous condition it appeared before the presentation of both stimuli. The stimuli and the cue disappeared together in all cases. A valid trial was one in which the cue and the response probe appeared in the same location, and an invalid trial was one in which the cue and the response probe appeared in different locations.*

3° eccentricity). In the sequential condition two gratings were presented one after the other in two different locations, and in the simultaneous condition the two gratings were presented at the same time. For all three trial types, the gratings were followed by noise masks appearing in the same locations as the gratings. Stimulus locations were selected randomly with the proviso that both stimuli had to be at separate locations. Stimulus orientation was selected pseudorandomly from one of 12 possible orientations (10°, 24°, 38°, 52°, 66°, 80°, 100°, 114°, 128°, 142°, 156°, 170°; with horizontal designated as 0°). Two gratings could not have the same orientation on the same trial.

In half of the experimental trials a spatial cue preceded the onset of the stimuli. In the simultaneous block type it appeared before the onset of both stimuli, and in the sequential block type it appeared either before the first stimulus or before the second stimulus, depending on the experiment. There was no spatial cue in the other half of the experimental trials or in the practice trials. The validity of the spatial precue differed by experiment. Participants were not made aware of the validity of the spatial cue, nor were they alerted to the presence of the cue in the instructions provided. In all experiments there were two different types of invalidly cued trials. Either the cue could appear at one of the two positions where neither Gabor would subsequently appear, or it could appear at the location where the Gabor that would *not* be probed for recall would appear. Where relevant, these types of invalid trials are distinguished in the analysis.

For all trials a white, 1.5° square appeared at the end of each trial and indicated the location of the grating that the participant was to use for their response. In addition, a grating [size: 1.2°; orientation: vertical (90°)] appeared in the centre of the screen and was used for participant responses. Participants rotated the response grating to match the orientation of the probed stimulus using four keys. The left and right arrow keys continuously rotated the response grating $\pm 1°$, and holding down the "ctrl" key while using the left and right arrow keys rotated the response grating exactly $\pm 1°$ on each key press. In all trials the probed location was selected randomly. Participants were instructed to keep their eyes on fixation and their fingers on the response keys throughout the experiment, and to respond as accurately as possible (responses were therefore unspeeded).

Data analysis

All analyses were conducted in R using the heplots (Fox, Friendly, & Monette, 2014), nlme (Pinheiro, Bates, DebRoy, & Sarkar, 2014), and multcomp (Hothorn, Bretz, & Westfall, 2008) packages. The ggplot2 package was used to create all plots (Wickham, 2009). The R scripts used to conduct the analysis are available upon request. The error between true orientation and judged orientation on each trial was calculated by subtracting the true orientation from the judged orientation and wrapping it to an interval between $-90°$ and $+90°$. No effects of bias were found for any condition in any experiment so the analysis of bias is not reported here.

EXPERIMENT 1

The purpose of the first experiment was two-fold: Would we replicate the results of Liu and Becker (2013) when a cue was introduced on some trials, and would there be evidence of an interaction between cue effects and memory effects? A 100% spatial cue was used to maximize the potency of the cue.

Method

Participants

Thirty-four students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design, and procedure

The validity of the precue was 100%. The practice trials consisted of 15 trials of each trial type, blocked, and with no spatial cue for a total of 45 practice trials. Following the practice trials, participants were presented with two superblocks each consisting of one 75 trial sequential block, and one 75 trial simultaneous block in random order for a total of 300 experimental trials. Participants were informed of the block type at the beginning of each block, and the experiment took approximately 30 min.

Results and discussion

One of the main results of Liu and Becker (2013) was a reduced error variance for orientation

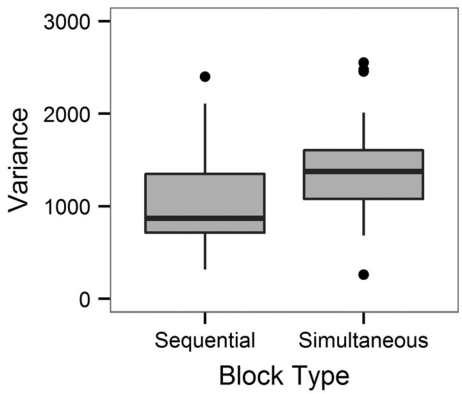

Figure 2. *When trials were uncued, error variance was lower on sequential than on simultaneous trials in Experiment 1.*

judgements on sequential trials. As a replication, we performed this analysis on our uncued trials (the trials that were identical to those of Liu & Becker, 2013). Figure 2 illustrates our replication, $F(1, 33) = 13.76$, $p < .001$, $\eta_P^2 = .29$. Orientation judgements on sequential trials were less variable. The magnitude of the variance we found was very similar numerically to that reported by Liu and Becker (2013).

Next, we directly compared response precision across block types with and without cueing. Our metric for quantifying precision was the median absolute deviation. This measure is preferable to the variance (or standard deviation) when data are not normally distributed (Gorard, 2005). It is less sensitive to outliers than is the variance (which measures the squared deviation) and has been used in prior work of this type (Anderson & Druker, 2013; Prinzmetal et al., 1998; Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997). The main effect of cueing on the median, absolute error was not significant, $F(1, 33) = 0.444$, $p = .51$; however, consistent with a difference between the effects of memory and attention on response variability there was an interaction between block type and cueing, $F(1, 33) = 5.131$, $p < .05$, $\eta_P^2 = .13$ (Figure 3). Post hoc analyses indicated that there was a trend of cueing reducing the median, absolute error only on simultaneous trials [simultaneous: $F(1, 33) = 3.472$, $p = .07$, $\eta_P^2 = .10$; sequential: $F(1, 33) = 1.095$, $p = .30$].

Because we used a 100% valid cue, we cannot evaluate from these data whether the principal effect of a cue may be to worsen performance when it is invalid. This might explain the failure to find a main effect for cueing. Furthermore, the nature of the sequential trials makes interpreting the absence of a cueing effect challenging. First, there are differences in stimulus onset asynchrony (SOA) when the target is the first stimulus and when it is the second stimulus. Previous work has demonstrated that the magnitude and direction of cueing effects is dependent on SOA (Posner, 1980). Secondly, it is possible that there is a floor effect because of the reduced variability on sequential trials.

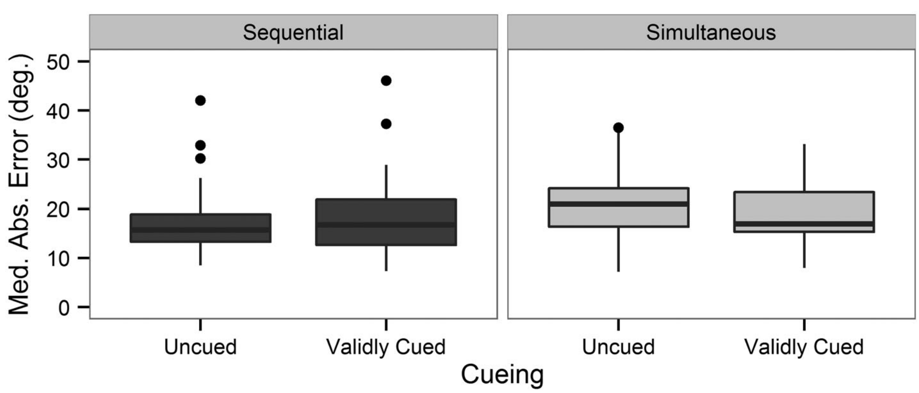

Figure 3. *Cueing reduced the median, absolute error (med. abs. error) only on simultaneous trials in Experiment 1.*

In summary, we have shown that variability was lower on sequential than on simultaneous trials, and that a 100% valid spatial precue may reduce errors on cued trials on simultaneous trials only. Consequently, we have preliminary evidence that memory and attention affect orientation judgements via different routes, and that attention may facilitate performance only when memory consolidation demands are high. In the next experiment we address the concern that the size of our cueing effect may be due to the absence of invalid trials.

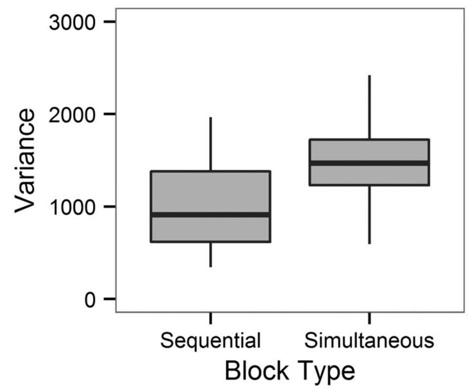

Figure 4. *Error variance was lower on sequential trials in Experiment 2.*

EXPERIMENT 2

In order to address the possibility that the effects of cueing are largely attributable to invalid cueing and to investigate the effects of cueing on sequential trials free from floor effects, Experiment 2 repeats the procedures of Experiment 1, but with an 80% valid cue.

Method

Participants

Thirty-five students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design, and procedure

The only difference between Experiment 1 and Experiment 2 was that the validity of the precue was 80% in Experiment 2.

Results and discussion

Two participants were removed because a technical problem resulted in the absence of invalid trials, and one participant was removed for responses indistinguishable from chance.

To evaluate consistency across experiments, we compared the variance of responses on uncued trials. We found results almost identical to those of Experiment 1. Variability of responses on uncued trials was lower for sequentially presented stimuli, $F(1, 33) = 41.11$, $p < .001$, $\eta_P^2 = .57$ (Figure 4).

The main effect of cueing on the median, absolute error was significant, $F(2, 62) = 35.57$, $p < .001$, $\eta_P^2 = .53$, as was the interaction between block type and cueing, $F(2, 62) = 9.787$, $p < .001$, $\eta_P^2 = .24$ (Figure 5a).

Visual inspection of Figure 5a shows that performance on sequential trials was generally better, and, as in Experiment 1, there was little difference between uncued and validly cued trials. In contrast, on simultaneous trials, validly cued trials reduced the magnitude of errors in addition to invalidly cued trials increasing it. The post hoc Tukey contrasts for the differences between the levels of cueing on sequential and simultaneous trials are provided in Table 1.

It is possible the absence of an effect of valid cueing on sequential trials may be explained by a floor effect; however, similar orientation judgement experiments (e.g., Anderson & Druker, 2013) have shown better performance with lower contrasts. Further, the standard deviations in the Liu and Becker (2013) study, which we replicate, are smaller (see below). Thus a floor effect seems unlikely to account for these data.

In summary, Experiment 2 confirmed that the effects of *predictive* spatial precues on orientation judgements are modulated by the demand on memory consolidation. When stimuli were presented sequentially, the consolidation of both

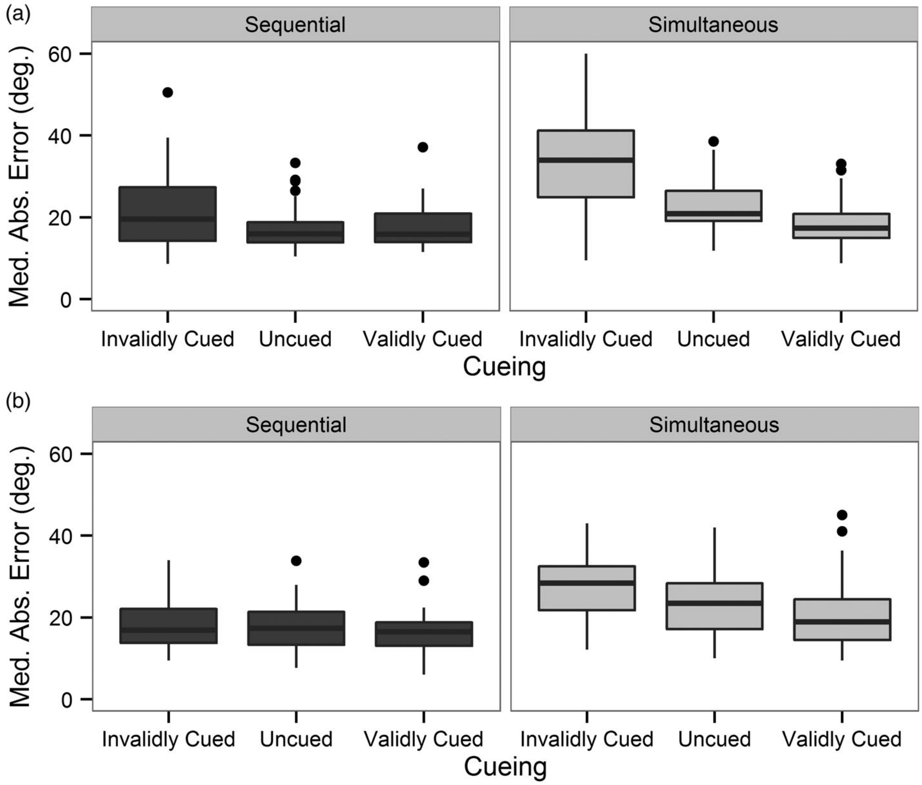

Figure 5. *Only invalid cues affected performance on sequential trials, whereas performance was affected by both invalid and valid cues on simultaneous trials in (a) Experiment 2 and (b) Experiment 3 (med. abs. error = median, absolute error).*

stimuli can take place. Then spatial cues do not *improve* performance, but they can worsen it. When demands are higher, because two stimuli must be consolidated simultaneously, spatial cues aid performance on valid trials and reduce it on invalid trials.

Table 1. *Linear Tukey contrasts on precision between the levels of cueing on sequential and simultaneous trials in Experiment 2*

Contrast	*Sequential estimate (z)*	*Simultaneous estimate (z)*
Uncued–invalid	−3.878 (−2.78*)	−9.88 (−5.23***)
Valid–invalid	−3.53 (−2.53*)	−14.42 (−7.63***)
Valid–uncued	0.35 (0.25)	−4.54 (−2.40*)

*$p < .05$. ***$p < .001$.

EXPERIMENT 3

So far we have demonstrated that predictive valid cues improve performance by reducing error magnitude on simultaneous trials, and that invalid cues reduce performance on both simultaneous and sequential trials. Predictive spatial cues engage a mixture of endogenous and exogenous attention, and so, not surprisingly, their effects are different from the strictly exogenous case of nonpredictive cues (Enns & Brodeur, 1989; Eriksen & Yeh, 1985; Johnson & Yantis, 1995; Jonides, 1980). In Experiment 3, we used a 50% nonpredictive spatial cue to isolate the effects of exogenous attention. Comparing Experiment 2 (80% valid cues) with Experiment 3 (50% valid cues) will permit us to assess how much endogenous mechanisms are contributing to the performance effects.

Method

Participants

Thirty-five students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design, and procedure

The only difference between Experiment 2 and Experiment 3 was that the validity of the precue was 50% in Experiment 3.

Results and discussion

Three participants were removed for performance indistinguishable from chance. As in Experiment 2, the main effect of cueing, $F(2, 60) = 16.01$, $p < .001$, $\eta_P^2 = .35$, and the effect of the interaction between block type and cueing, $F(2, 60) = 3.925$, $p < .05$, $\eta_P^2 = .12$ (Figure 5b), were significant and appear similar.

Experiment 3 demonstrated that the different effects of the cue between low and high memory consolidation demands are not dependent on the cue being predictive. Valid cueing did not improve performance on sequential trials whereas it did on simultaneous trials, regardless of whether the cue provided any spatial information about target position. In all cases, and regardless of memory demands, invalid cues worsen performance.

EXPERIMENT 4

The first three experiments taken together suggest that, when used in difficult tasks with multiple stimuli, attentional cues *improve* performance only when the demand on memory consolidation is high. We have also shown that predictive and nonpredictive cues alike can help prioritize stimuli for processing, and that spatial cues cannot be ignored, even when they do not seem to give us any valid information about target locations.

Direct comparisons between sequential and simultaneous trials in these first three experiments is complicated, however, by the fact that the cue always appeared before the onset of the first stimulus, regardless of whether the participant was to respond to the first or second stimulus in a sequential trial. This experimental structure keeps the overall timing of sequential and simultaneous trials the same, but at the expense of inducing different cue—target timings for sequential trials when the target is the first or second stimulus presented. An alternative approach is to present the cues sometimes before the first stimulus of a sequential trial, and sometimes before the second. This would keep cue–target timings the same. This is what was done for the next two experiments where we repeat the manipulations of predictive (80% valid; Experiment 4) and nonpredictive (50% valid; Experiment 5) cueing.

Method

Participants

Thirty-four students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design, and procedure

In Experiment 4 there were two sequential block types. In one type the cue appeared before the onset of the first stimulus, and in the other the cue appeared before the onset of the second stimulus. Simultaneous trials were unchanged. The spatial precue was 80% valid. Following the practice trials, participants were presented with two superblocks each consisting of one 100-trial sequential block with the cue appearing before the first stimulus, one 100-trial sequential block with the cue appearing before the second stimulus, and one 100-trial simultaneous block in random order for a total of 600 experimental trials. Participants were informed of the block type (without information about the cue for sequential trials) at the beginning of each block, and the experiment took approximately one hour.

Results and discussion

One participant was removed for performance indistinguishable from chance. To assess the effect of cueing for targets appearing in the first or second position without different cue–target timings we began by analysing only those trials where the cue and target appeared in the same temporal epoch. That is, if the stimulus that we would eventually ask the participant to report on was to be the first one shown, we only include trials when the cue appeared before the first stimulus, and if the stimulus to be reported was to be the second one shown we only include those trials when the cue appeared before the second stimulus. This gives a consistent timing for validly cued trials. It also yields two types of invalid trials. Either we cue the location of empty space—that is, a location where no stimulus is shown on that trial—or invalidly cue the "wrong" stimulus—that is, the cue appears at the same spatial position as the stimulus that the participant will *not* be asked to judge.

When evaluating the effects of cueing, we again find a main effect of cueing, $F(2, 64) = 38.1$, $p < .001$, $\eta_P^2 = .54$, and a Block Type × Cueing interaction, $F(4, 128) = 7.723$, $p < .001$, $\eta_P^2 = .19$ (Figure 6a), on the median, absolute error.

Visual inspection of Figure 6a demonstrates that the pattern of results seen in Experiment 4 largely replicate the results of Experiment 2 (Figure 5a), namely that a predictive spatial precue improved performance on valid trials when they were simultaneous and hurt performance on both invalidly cued simultaneous trials and sequential trials. Furthermore, it appears that performance on valid trials is the same across trial types, implying that spatial attention selects information for processing when multiple stimuli have to be consolidated at the same time by giving priority to the attended stimulus. This assertion is supported by the post hoc Tukey contrasts provided in Table 2. When the spatial information is absent or wrong, performance is hurt. When the demand on memory

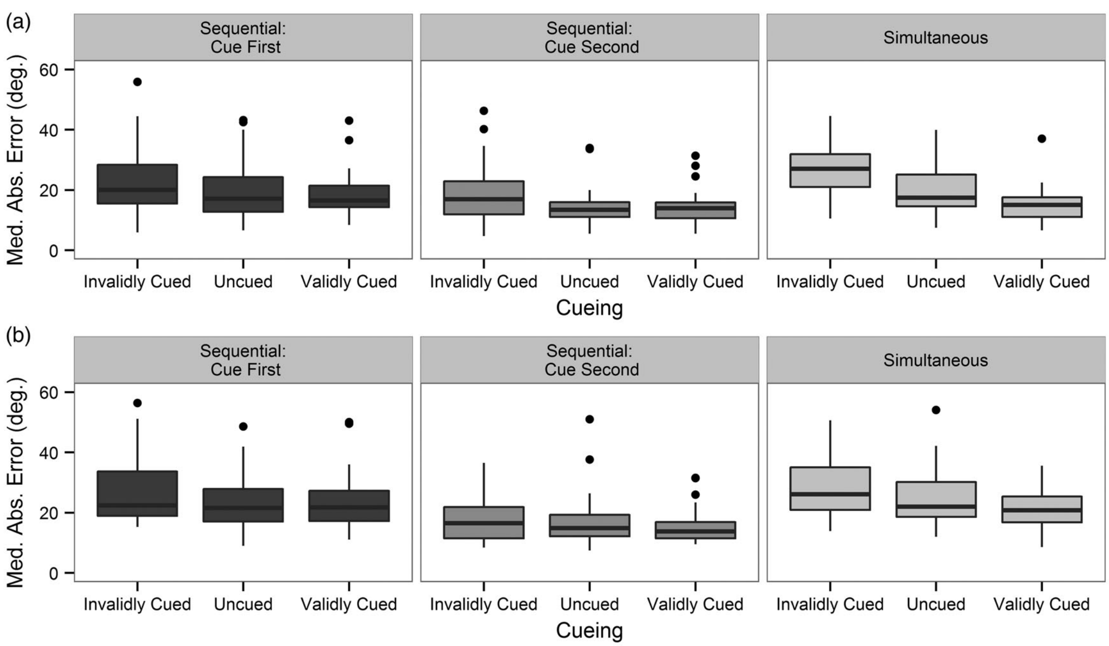

Figure 6. *(a) The results of Experiment 4 largely replicate the results of Experiment 2 (Figure 5a), namely that the predictive spatial precue affected performance for simultaneous trials, but not as much so for sequential trials. (b) This result is the same for Experiment 5 and Experiment 3 (Figure 5b) (med. abs. error = median, absolute error).*

Table 2. *Linear Tukey contrasts on precision between block types on invalid, uncued, and valid trials in Experiment 4*

Contrast	*Invalid estimate (z)*	*Uncued estimate (z)*	*Valid estimate (z)*
Seq2–Seq1	−3.96 (−2.24)	−5.67 (−4.80***)	−4.40 (−5.10***)
Simul.–Seq1	4.73 (2.67*)	0.16 (0.14)	−3.51 (−4.10***)
Simul.–Seq2	8.69 (4.91***)	5.84 (4.94***)	0.88 (1.02)

Note: Seq = sequential; simul. = simultaneous.
*$p < .05$. ***$p < .001$.

consolidation is high, as when the stimuli appear on the screen together for a brief duration, attention must be reoriented between the two potential target stimuli.

Up to this point we have demonstrated consistent differences of the effects of a spatial precue between the level of the demand on memory consolidation, that these differences are not dependent on cue validity, and that invalid trials make performance worse across the board. This begs the question of whether the type of invalid trial is relevant and whether that depends on the temporal position of the spatial precue. Figure 7a suggests that there was no difference between when the

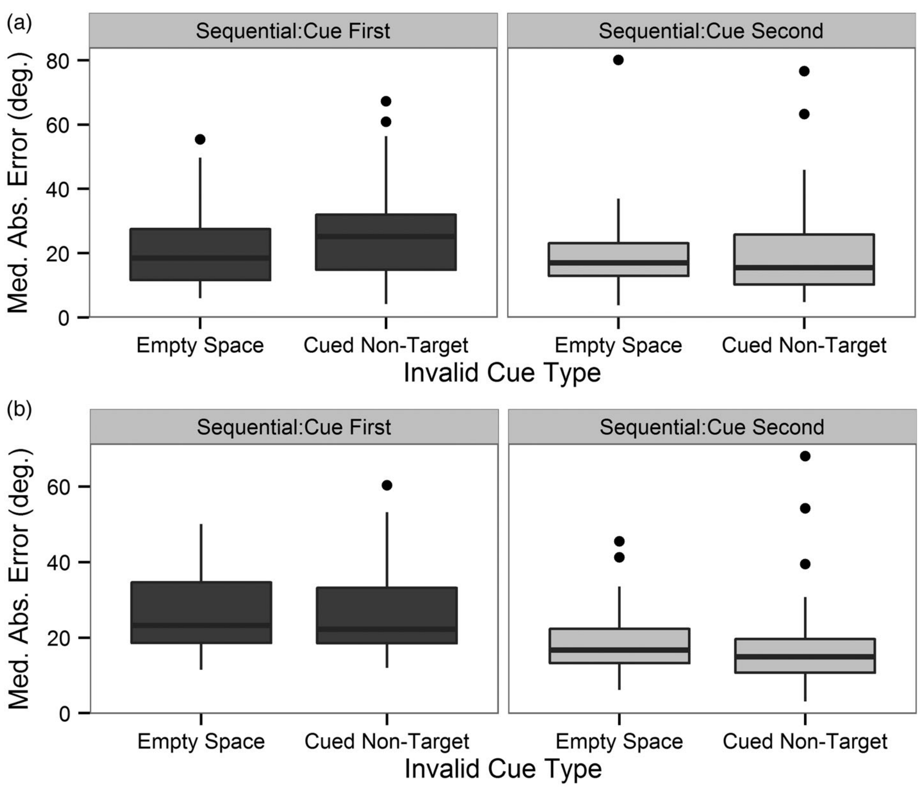

Figure 7. *Performance was the same in (a) Experiment 4 and (b) Experiment 5 when the invalid cue appeared in the location of the nontarget stimulus and when it appeared in empty space (med. abs. error = median, absolute error).*

invalid trial was one where the nontarget stimulus was cued or where empty space was cued. Indeed, the main effect of invalid cue type on the median, absolute error of orientation judgements was not significant, $F(1, 32) = 1.831$, $p = .19$, and neither was the interaction with block type, $F(1, 32) = 1.103$, $p = .30$.

EXPERIMENT 5

In Experiment 4 we demonstrated that the temporal position of the cue was irrelevant for predictive cues and that the results largely replicated the results of Experiment 2. In this final experiment, we turn to nonpredictive cues.

Method

Participants

Thirty-five students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design, and procedure

The only difference between Experiment 4 and Experiment 5 was the validity of the spatial precue. The cue was 50% valid.

Results and discussion

One participant was removed for performance indistinguishable from chance. To keep the timing consistent for validly cued trials, only the trials on which the cue and the target appeared in the same temporal epoch were included in this analysis.

The main effect of cueing on the median, absolute error, $F(2, 66) = 18.73$, $p < .001$, $\eta_P^2 = .36$, and the interaction between cueing and block type were significant, $F(4, 132) = 3.633$, $p < .01$, $\eta_P^2 = .10$ (Figure 6b). The results replicate those of the prior experiments—namely, that the difference in the effect of the cue between sequential and simultaneous block types was not dependent on the predictive value of the cue, that invalid trials hurt performance universally, and that valid trials help performance only when the demand on memory consolidation was high.

The results across the five experiments have been quite consistent, and so as one final demonstration we collapsed the data across all experiments and found that the main effect of cueing, $F(2, 68) = 10.561$, $p < .01$, and the interaction between block type and cueing, $F(2, 68) = 6.536$, $p < .01$ (Figure 8), were significant. The result is consistent with the results of all five experiments: Spatial precues reduce performance universally on invalid trials, but only improve performance on valid trials when the demand on memory consolidation is high.

Finally, we evaluated whether the type of invalid cue mattered and replicated the result of Experiment 4 that there was no difference in performance between when the invalid cue cued empty space and when the nontarget stimulus was cued, $F(1, 33) = 0.39$, $p = .54$; there was as well no interaction with block type, $F(1, 33) = 0.285$, $p = .60$ (Figure 7b).

MIXTURE MODEL ANALYSIS (EXPERIMENTS 1, 2, AND 3)

In order to evaluate more specifically the mechanisms behind the memory consolidation effect, operationalized by presenting the stimuli sequentially or simultaneously, Liu and Becker (2013) reported a mixture model analysis. They fitted their error data to a mixture that included a uniform component (to capture guessing) and a von Mises function to capture response standard deviation. The mixture model had three free parameters: the mean of the von Mises, the width of the von Mises, and the mixture proportion. Changes in the first term as a function of block type would indicate differences in response bias, the width term would reflect differences in response standard deviation, and the mixture coefficient would reflect the probability of guessing. The standard deviation parameter is descriptively referred to as a model-based precision by Liu and Becker (2013); however, to avoid confusion between the model-free precision results and the model-based precision

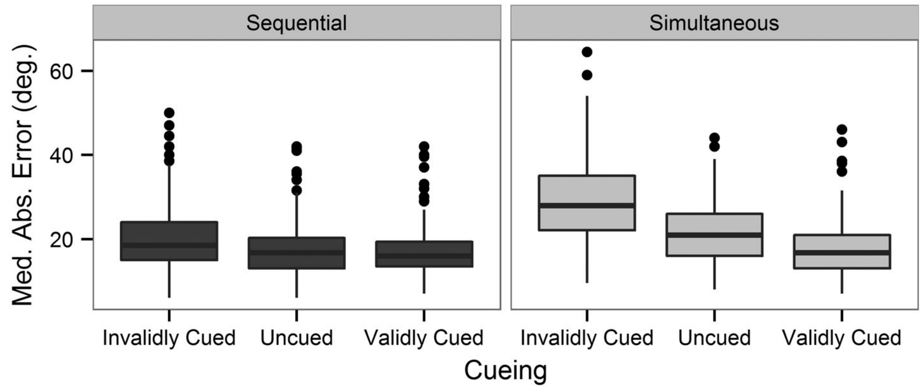

Figure 8. *Data from all five experiments amalgamated together (med. abs. error = median, absolute error).*

results reported here, we refer to the latter as the standard deviation of the model fit.

Liu and Becker (2013) reported that the only parameter to change between the sequential and simultaneous trials was the guessing component, and they concluded that memory consolidation has its principal effect on error variability by reducing the probability of guessing and not by affecting the judgement standard deviation per se. We repeated the procedure used by Liu and Becker (2013) as another test of the replicability of their results, but we also included the cued trials to elaborate on the dependence of memory and attention observed in the prior analysis of precision. We excluded Experiment 4 and Experiment 5 from this analysis to avoid redundancy.

There is considerable discussion on the right way to model memory (Ma, Husain, & Bays, 2014; van den Berg, Awh, & Ma, 2014; van den Berg, Shin, Chou, George, & Ma, 2012). Particularly contentious is the debate on whether the mixture model employed by Liu and Becker (2013) is a good way to model such data. The parameters can be difficult to interpret as they depend on the validity of the model. It is sometimes the case that the residuals of the mixture model are structured, and this poses a challenge to interpreting the meaning of any differences in model parameters. It is therefore important to emphasize that we do not wish to draw conclusions about the structure of memory or the underlying processes. Rather, we have employed it as a descriptive tool to elaborate on the behavioural results reported above.

We fitted a mixture model of the above type to individual participant data using a custom script written in R (available upon request). We evaluated standard deviation and guessing parameters with 2 (block type: sequential vs. simultaneous) × 3 (2 in Experiment 1; cueing: invalid vs. uncued vs. valid) analyses of variance (ANOVAs). We calculated the residuals and found them to be small (less than .0015) so we have not reported them here.

With respect to memory consolidation, we replicated Liu and Becker (2013). In Experiment 1 and Experiment 2, participants made more guesses on simultaneous trials than on sequential trials [E1: $F(1, 33) = 20.92$, $p < .001$, $\eta_p^2 = .39$; E2: $F(1, 31) = 11.08$, $p < .01$, $\eta_p^2 = .26$], and standard deviation did not significantly differ between block types [E1: $F(1, 33) = 0.377$, $p = .54$; E2: $F(1, 31) = 3.459$, $p = .07$]. In Experiment 3, the guessing parameter was not significantly affected, $F(1, 30) = 0.747$, $p = .39$, but the standard deviation parameter was, $F(1, 30) = 16.33$, $p < .001$, $\eta_p^2 = .35$. It is possible that the interaction between the nonpredictive spatial cue and the consolidation condition affected the overall distribution of errors differently when the cue was nonpredictive compared to when it was predictive.

With respect to cueing, the main effect of cueing on guessing was not significant when the cues were predictive [E1: $F(1, 33) = 0.898$, $p = .35$; E2: $F(2, 62) = 0.739$, $p = .48$], but it was significant when the cues were nonpredictive [E3: $F(2, 60) = 5.749$, $p < .01$, $\eta_p^2 = .16$]. The post hoc linear Tukey contrasts indicated that only the difference between invalid and valid trials was significant (*estimate* = .13, $z = 3.263$, $p < .01$). There was no main effect of cueing on the standard deviation in any experiment [E1: $F(1, 33) = 4.119$, $p = .05$; E2: $F(2, 62) = 2.849$, $p = .07$; E3: $F(2, 60) = 0.322$, $p = .73$].

There was a trend, however, for cueing to affect standard deviation when the cues were predictive, and it may not have reached significance because of undetectably small differences on sequential trials. Indeed, the interaction between block type and cueing on standard deviation (Figure 9a and Figure 10a) was significant when the cues were predictive [E1: $F(1, 33) = 7.81$, $p < .01$, $\eta_p^2 = .19$; E2: $F(2, 62) = 6.628$, $p < .01$, $\eta_p^2 = .18$] and not when they were nonpredictive [E3: $F(2, 60) = 1.692$, $p = .19$]. When the cues were predictive, the main effect of cueing on standard deviation was not significant on sequential trials [E1: $F(1, 33) = 0.138$, $p = .71$; E2: $F(2, 62) = 1.235$, $p = .30$], but it was significant on simultaneous trials [E1: $F(1, 33) = 11.72$, $p < .01$, $\eta_p^2 = .26$ (Figure 10a); E2: $F(2, 62) = 5.771$, $p < .01$, $\eta_p^2 = .16$ (Figure 10b)]. The standard deviation was lower on cued trials than on uncued trials in Experiment 1, and lower on valid trials than on invalid trials in Experiment 2 (Table 3).

With respect to guessing, the interaction between block type and cueing (Figures 9b and 10b) was not significant when the cues were predictive [E1: $F(1, 33) = 1.88$, $p = .18$; E2: $F(2, 62) =$

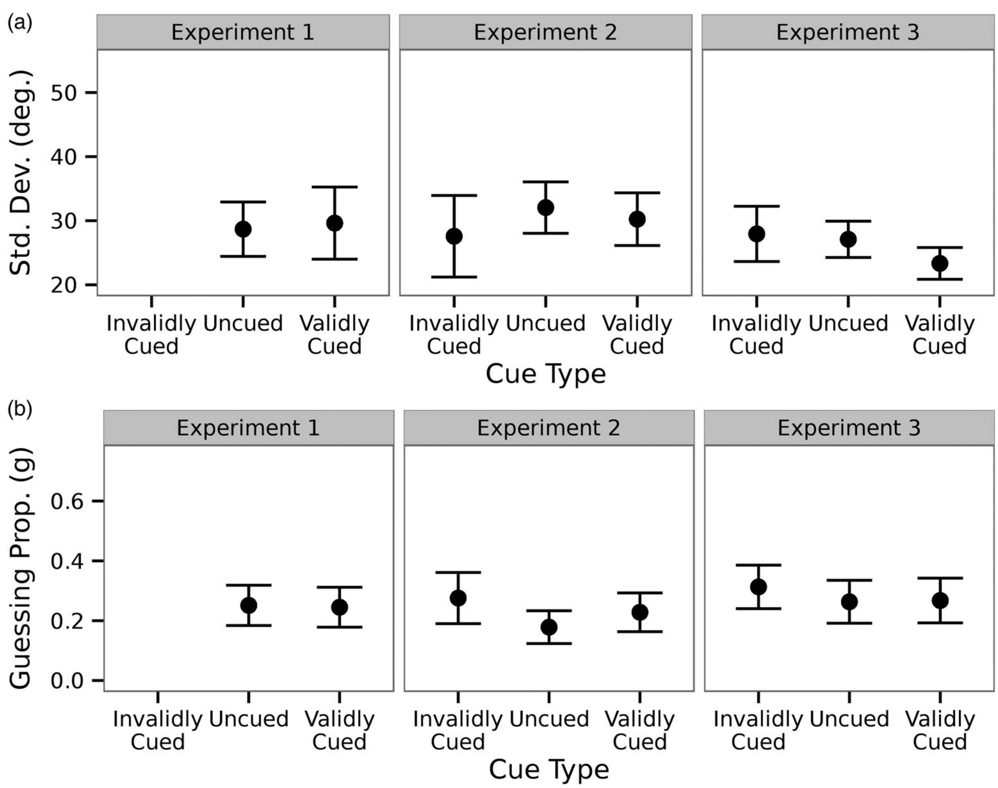

Figure 9. *Mixture model fit results on sequential trials for (a) standard deviation (std. dev.) and (b) guessing (prop. = proportion).*

Table 3. *Linear Tukey contrasts of the mixture model standard deviation between the levels of cueing on simultaneous trials in Experiment 2*

Contrast	*Estimate (degrees)*	z	p
Valid–uncued	−7.44	−1.54	.27
Invalid–uncued	9.18	1.86	.15
Invalid–valid	16.04	3.39	<.01

1.069, $p = .35$], but it was significant when the cues were nonpredictive, $F(2,\ 60) = 5.815$, $p < .01$, $\eta_p^2 = .16$. When the cues were nonpredictive, the main effect of cueing on guessing was not significant for sequential trials, $F(2,\ 60) = 1.926$, $p = .16$, but it was significant for simultaneous trials, $F(2,\ 60) = 6.549$, $p < .01$, $\eta_p^2 = .18$. Participants made fewer guesses when the cue was valid than on uncued and invalid trials (Table 4).

In summary, the mixture model results indicate that the mechanism of the effects on precision depend on whether the cues are predictive or nonpredictive. For predictive cues, precision was affected because errors were overall more (valid) or less (invalid) concentrated at the centre of the distribution. For nonpredictive cues, guessing was affected because the likelihood the target would be consolidated was improved, which reduced guessing on valid trials and increased guessing on invalid trials.

GENERAL DISCUSSION

The effects of memory and attention on perceptual judgements for orientation seem to interact. We replicated the memory effects reported by Liu and Becker (2013), namely that variance was lower on sequential trials than on simultaneous trials, and that the mixed model fitting showed the salient difference to be guessing proportion.

With respect to attention, the effects are more complex. In cases where spatial cues are 100% predictive it is not possible to compare validly and invalidly cued trials, but the fact that valid cueing facilitated performance on simultaneous trials and did not facilitate it on sequential trials suggests that valid cueing only benefits performance when it can prioritize stimuli for consolidation. Indeed, work by Yeh, Yang, and Chiu (2005) supports this claim. In their experiments participants were required to detect either changes in features or changes in conjunctions of features. Attentional shifts were manipulated during the retention interval. Central and peripheral letter cues had similar impacts on the detection of feature and conjunction changes, suggesting that the cues prioritized the selection of information for consolidation rather than improving the binding of features. Furthermore, postcues improved detection only at short delays during which consolidation occurred.

This result appears to contradict prior work demonstrating increased precision on valid trials in the case of a single stimulus (Anderson & Druker, 2013). Both multiple sequential stimuli and single stimulus orientation judgement experiments involve consolidating one target at a time, and yet we did not find the valid cueing effects typically found with single stimuli experiments on sequential trials. The fact that precision was reduced on invalid trials rules out the possibility that participants were ignoring the cues. Furthermore, excluding the effect of SOA in Experiment 4 and Experiment 5 still did not produce valid cueing effects on sequential trials, and there was no difference between the effects of a predictive and nonpredictive cue, suggesting that the effect of the cue was not mediated by top down processes. Our results, therefore, suggest that attention and memory consolidation are not separable and independent effects in cases where multiple things have to be remembered. Rather, they are dependent and interacting, and this effect does not appear to be influenced by top down processes.

The aggregate effects on precision were independent of cue validity, but the mixture model parameters revealed differential effects. When the cues were predictive, differences in performance were explained by differences in the standard deviation of the error distributions. In contrast, when the cues were nonpredictive, differences in precision were explained by differences in guessing. A

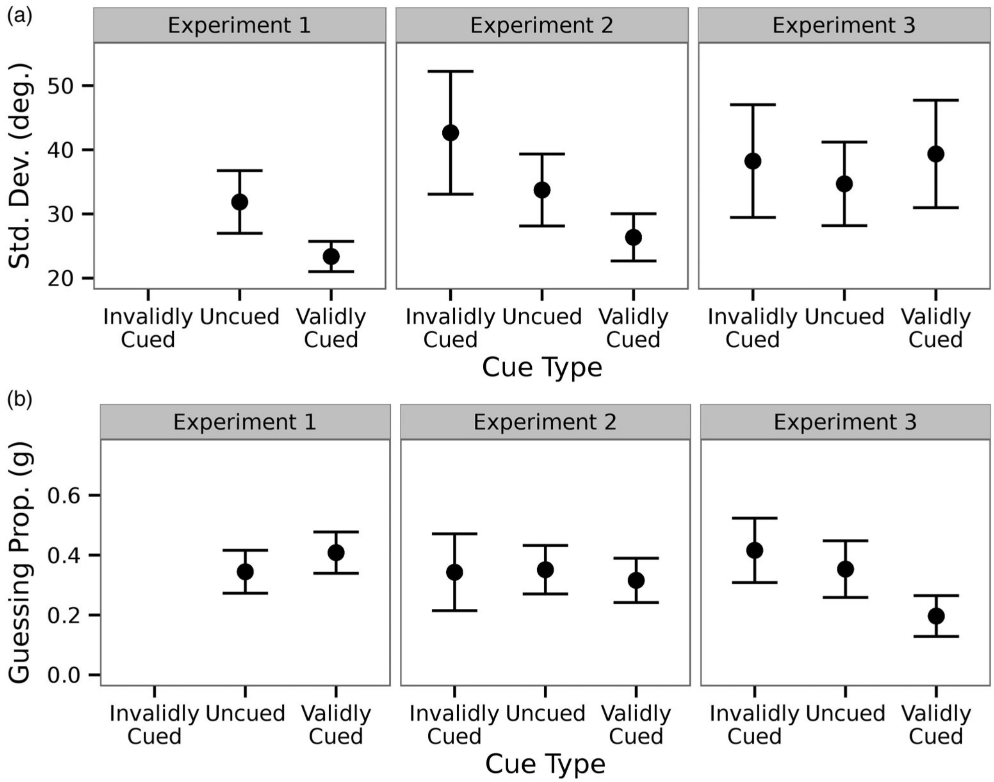

Figure 10. *Mixture model fit results on simultaneous trials for (a) standard deviation (std. dev.) and (b) guessing (prop. = proportion).*

changing mechanics of cue effects with cue validity is consistent with the large amount of data showing that we implicitly monitor our environment for statistical regularity (Fiser & Aslin, 2001; Perruchet & Pacton, 2006; Saffran, Aslin, & Newport, 1996; Turk-Browne, 2012; Turk-Browne, Scholl, Chun, & Johnson, 2009).

Also noteworthy is the fact that precision on valid trials was the same for sequential and simultaneous trials, whereas precision on invalid trials was much worse on simultaneous trials than on sequential trials. Most of the effect of the cue was therefore in making performance worse on invalid trials. This might be explained by the fact that attentional effects are at least in part mediated by the inhibition of distractors (Shiu & Pashler, 1994). In cases where multiple stimuli must be consolidated at the same time, and attention is validly oriented, the nontarget stimuli is suppressed, and consolidation occurs as it would in the case of a single stimulus. As a result, performance is much worse on invalid trials because stimuli in uncued locations are suppressed as presumed distractors.

In summary, we have provided evidence from a single experimental task and using a common analytic procedure that memory and attention have interacting effects on perceptual judgements;

Table 4. *Linear Tukey contrasts of the mixture model guessing proportion between the levels of cueing on simultaneous trials in Experiment 3*

Contrast	*Estimate (degrees)*	z	p
Valid–uncued	−9.17	−2.51	<.05
Invalid–uncued	3.44	1.00	.58
Invalid–valid	12.61	3.51	<.01

performance was facilitated by a valid cue only on trials where the display consisted of multiple stimuli. When the display consisted of a single stimulus, valid cueing had no effect on precision, but invalid trials reduced precision. Further, we demonstrated that the precision effects of spatial attention on memory consolidation were not dependent on cue predictability; however, the mechanism by which spatial attention affects precision may be dependent on how we implicitly monitor our environment for statistical regularities.

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