Investigating stimulus-driven selective attention inside visual working memory

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Finally, I want to thank the person reading this. Master's theses are not often written under the delusion that anyone will ever actually read all 50-something pages. To any dear reader who intends to read the entire thing I say: good luck.

Abstract

Multiple objects can exist within (visual) working memory simultaneously, and internal selective attention is required to select amongst those objects. It is known this internal selection can occur in a goal-driven manner (Griffin & Nobre, 2003; van Ede et al., 2019), but the question remains whether this can also occur in a stimulus-driven manner. To answer this question, van Ede et al. (2020) developed a retrocue visual working memory task. They were able to induce attentional shifts with a completely uninformative retrocue, an effect that is best explained by the occurrence of stimulus-driven internal attention. Using eye-tracking, van Ede et al. showed that these attentional shifts were accompanied by a shift in gaze position towards the original location of the currently active memory item. Liu et al. (2022) showed that an internal attentional shift is often (also) accompanied by a bias in microsaccade direction.

However, the retrocue employed by van Ede et al. was only completely uninformative in one third of all trials, creating the possibility that the retrocue retained some implied informational value for participants. Our main research question therefore is: is a completely uninformative cue capable of and sufficient for creating an involuntary attentional-capture effect? If so, is this again reflected in an ocular signature consisting of a bias in gaze position and microsaccade direction? And is the behavioural effect that results from the attentional capture due to a benefit to the cued memory item, a cost to the uncued memory item, or a combination of both?

To answer these questions, the visual working memory task from van Ede et al. (2020) was employed after changing it in two critical ways. Based on the previous research we expected to find a behavioural attentional-capture effect, by observing less reproduction error and/or shorter decision times when the capture cue colour-matched the eventually probed item. We also expected that this behavioural effect would be accompanied by both a bias in gaze position and microsaccade direction towards the cued memory item.

Two separate experiments were performed for this research, which only differed in the shape of the capture cue. Experiment 1 produced no significant effect of capture cue congruency on decision times or accuracy, and this was accompanied by an extremely small, but significant, gaze bias. No significant microsaccade bias was found. Experiment 2 produced a significant effect of congruency on decision times, but not on accuracy: participants responded faster in congruent trials than in both neutral and incongruent trials. On group-level, this behavioural effect was again accompanied by a small, but significant, gaze bias, and no significant microsaccade bias was found.

The relationship between behavioural effect and ocular bias was further investigated by calculating a decision time effect size and a microsaccade bias effect size. A median-split of decision time effect size showed a significant microsaccade bias was present in the above-median decision time effect group. This microsaccade bias occurred within the expected timeframe, as based on previous research by Liu et al. (2022).

We concluded that a completely uninformative capture cue is capable of and sufficient for creating an involuntary attentional-capture effect within a visual working memory task. In a subset of participants this was also reflected in a significant bias in microsaccade direction, but this did not occur at a group-level. Finally, it seems the behavioural effect is due to a benefit for cued items, at no cost to uncued items. The current experiment complements earlier work by providing further proof that stimulus-driven internal attention does indeed exist and is sometimes accompanied by an ocular signature, consisting of at least a microsaccade direction bias. This research emphasises that the external world plays an important role in shaping the contents of our mind.

Keywords

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Introduction

Intuitively, we talk about the mind as if it consists of separate systems, such as memory, perception and attention. Studying these supposedly separate systems is one of the main ways in which we attempt to investigate the whole that comprises these parts. Therefore, understanding human thought and behaviour is at least partially reliant on understanding attention and memory, and particularly any interactions that might occur between the two. The following pages therefore introduce the concept and taxonomy of the two cognitive systems that form the main subjects of the current work: (visual) working memory and attention. Using these definitions, we will be able to study how attention and working memory interface and interact.

(Visual) Working memory

The concept of memory includes every system in the mind that concerns itself with the encoding, retention and retrieval of information (Purves et al., 2013). One of these multiple forms of memory is known as working memory. Working memory refers to the temporary retention of information in a limited capacity (Baddeley, 2003; Chai et al., 2018). In the broader sense of the word, of course all information in the mind is stored only temporarily (despite how badly we sometimes wished the opposite), but temporary in this sense refers to the order of mere seconds. One important aspect of working memory, as the term is used by cognitive psychology and neuroscience, is the focus on the *manipulation* of information, as well as the storage (D'esposito et al., 1995; Smith & Jonides, 1999). For instance, working memory is extremely important for our ability to perform arithmetic (Cragg et al., 2017).

Within working memory even more sub-distinction can be made, visual working memory being one of them. Visual working memory refers to the impermanent storage of visual information (Baddeley, 2003). While this form of memory has a very limited capacity, it's relatively robust to subsequent stimuli and a visual working memory can remain active for many seconds (Shin et al., 2017). Because of these characteristics, visual working memory allows us to hold past visual percepts available, which is especially useful if those past percepts are expected to become relevant for guiding future behaviours.

However, in order to actually use any of the information stored in memory, some form of attention is required. But what exactly is attention?

Attention

The concept of attention is best explained in the words of William James (1890):

> *"Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others."* (p. 369)

William James immediately demonstrates that at the very core of attention is the ability to select certain information, while simultaneously neglecting the rest. It is precisely this selection of information that Chun et al. (2011) choose to form the basis of their taxonomy of attention. They propose a taxonomy of attention "*based on the types of information that attention operates over*", often referred to as the *target* of attention. Simply put, the target of attention is "the thing your attention is focussed on".

When multiple trains of thought co-occur, as William James describes in the previous quote, attention can be directed to one of them: this is a clear example of attention with an *internal* target. Internal attention always selects internally generated information, such as task rules, responses, or anything from memory. Conversely, the target of attention is often also located outside of ourselves, for instance when selecting sensory information. This type of attention is called *external* attention, because it has an external target. This form of attention selects anything from modality-specific input, to locations in space, and points in time.

However, this is not the only possible framework that can be used to describe different forms of attention. A second taxonomy of attention can be made based on the *source* of attention (Corbetta & Shulman, 2002; Katsuki & Constantinidis, 2014; Yantis & Jonides, 1990). The source of attention refers to the event or stimulus that leads to attention being paid to something in the first place. There are of course many possible sources of attention, but broadly speaking attention can be stimulus-driven or goal-driven. This distinction is often also referred to as, respectively, bottom-up vs. top-down attention, exogenous vs. endogenous attention, or involuntary vs. voluntary attention. An example of this distinction can be easily imagined: if someone asks you to *voluntarily* direct your attention somewhere, this is an example of goal-driven attention. Conversely, the sound of a glass shattering on the floor might draw your attention *automatically*.

The vigilant reader will have noticed that both previous examples of attention included an external target of attention. This is not by pure coincidence: external attention has been studied for far longer and far more often than internal attention, simply because studying external attention is more straightforward. A classic example of an external attention paradigm is the visual search task: in this task participants search for a target amongst many distractors (Wolfe, 2020). This specific task allows for many manipulations: the number of distractors, the defining feature of the target, the distracting features of the distractors, location, and so on.

All these manipulations have led to the discovery of something called the "pop out" effect, which refers to the target differing so saliently from the distractors that it seems to "pop out" at the observer. This effect mainly occurs when the target differs from the distractors within a limited set of features such as colour, size or motion. For example, in figure 1A the target is incredibly easily discerned from the distractors, while in figure 1B, finding the target requires an active search strategy. This pop out effect is often seen as a classic example of stimulus-driven attention, since it draws attention to the object automatically. Similarly, a scene which requires an active search strategy requires the use of goal-driven attention, since participants will only find the target if it is their goal to do so.
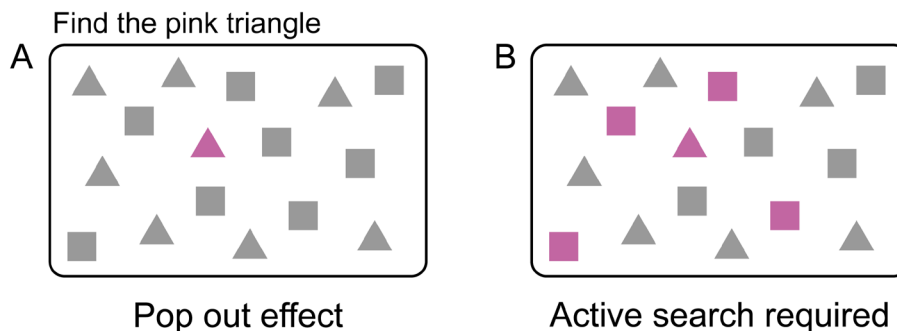

Figure 1: stimulus-driven vs. goal-driven external attention. *The current example shows how a "pop out" effect can occur in a standard visual search paradigm when the target differs saliently enough from the distractors. The target in both cases is the pink triangle.*

But can we ascertain different types of attention are employed in the previous example? The canonical answer to this is based on response times (Wolfe, 2020). When participants are asked to look for the target object in a scene with a pop-out target (as in figure 1A), their response time is roughly independent of the number of distractor items in the scene. Conversely, when the target requires an active search strategy, response times increase linearly with the number of distractors. Moreover, if the target is suddenly not present, the active search strategy becomes very slow, since all items need to be checked before the participant is sure there is no target, but the response time to the "pop out" scene remains almost constant. Bear in mind that in all of these cases the target remains an external object. These behavioural data therefore prove that external attention can be both stimulus-driven and goal-driven.

In other words, these examples allow us to see that when attention is *directed externally*, the source of that attention can be both *internal* (goal-driven) or *external* (stimulus-driven). This implies both taxonomies of attention can be overlaid to create a two-by-two organisation of attention (figure 2). However, this arrangement immediately begs one important question: if external attention can be split-up into goal-driven external attention and stimulus-driven external attention, is the same true for internal attention?
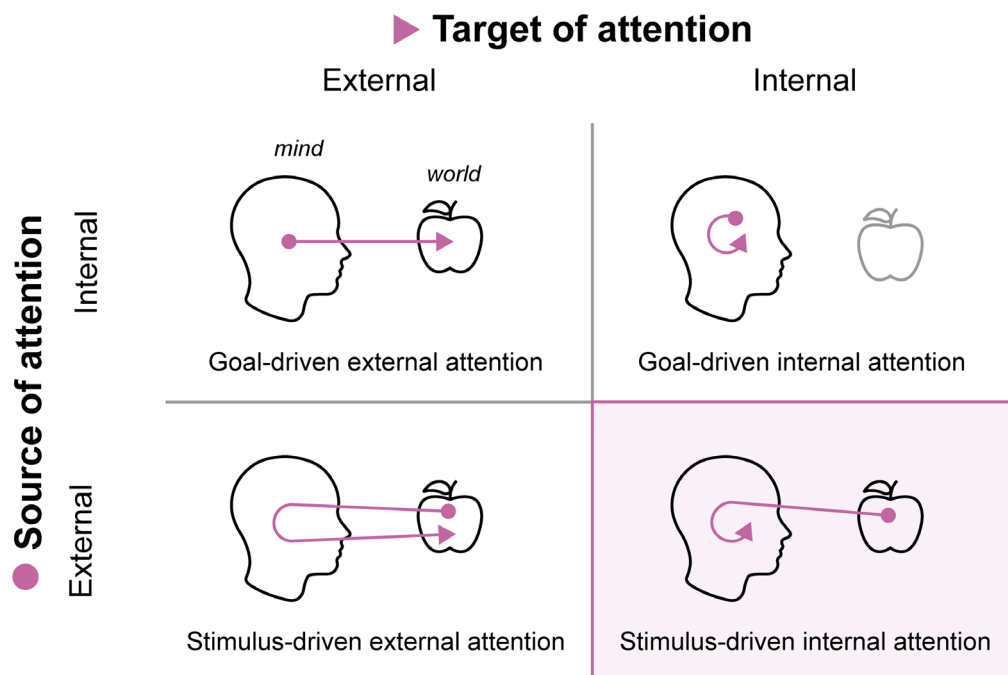

Figure 2: taxonomy of attention based on different sources and targets. *Each quadrant shows how external vs. internal sources and targets of attention can combine to produce distinct forms of attention.*

Goal-driven internal attention

We can first establish that goal-driven internal attention does not only exist, it has been studied for at least twenty years now. One example of this is a study conducted by Griffin & Nobre (2003), which aimed to investigate whether individuals can orient selective spatial attention to internal representations in working memory, similar to how they can orient attention to external perceptual stimuli. To this end, they conducted two behavioural experiments that compare cueing effects of pre-cues and retro-cues. By definition, pre-cues appear before the target item is displayed, while retro-cues are shown afterwards.

The use of pre-cues allows for selection of external stimuli, since when the stimuli appear, the participant is already aware of which one is the target. Contrarily, the use of retro-cues requires selection of internal representations. The use of a retro-cue means no physical representation of the stimulus array exists when the target is cued, and therefore the entire stimulus-array must be committed to memory beforehand. The results of both behavioural experiments demonstrated equivalent behavioural costs and benefits for pre-cues and retro-cues, suggesting that attention can be directed similarly to internal representations and external stimuli.

Another example can be found in a study by Souza et al. (2015), who found that refreshing memory traces through directional cues improved retrieval of items from visual working memory. These directional cues were displayed *after* the original stimuli were gone. Moreover, the behavioural benefit of refreshing memory items happened in a repetition-dependent manner: items that were refreshed twice were reproduced with even less error than items that were refreshed only once. Crucial to this experiment was that participants were explicitly instructed to think of the item the directional cue indicated. Participants were still aware these cues did not necessarily indicate which item would eventually be probed, but they were told that thinking of the cued item was part of the main task.

Based on these findings, it seems clear that goal-driven attention can be internally directed and used to select internal representations. However, all of the examples we have seen so far rely on some behavioural measure to prove attention was directed to a particular target. This is the main obstacle within attentional research: rigorously studying attention requires knowing for certain what someone is thinking of, however, mind-reading is unfortunately not a possibility yet in most labs. We are therefore forced to decipher the contents of mind through proxies, which inherently leads to much less reliable data. However, the reliability of your data can be increased by combining multiple proxies from different modalities (Ye et al., 2021).

This approach to attentional research was recently employed by van Ede et al. (2019), who showed a link between gaze position and attentional focussing in memory. Van Ede et al. developed a visual working memory task in which participants memorised the orientations of two coloured, tilted bars (see figure 3). After a short delay, a probe cue was used to indicate of which bar the orientation should be reproduced. Using eye-tracking, they showed that participants tended to shift their gaze position towards the original location of the currently active memory item, despite these items not being currently displayed. This "gaze towardness" effect occurred between 400 ms and 1000 ms after a cue was shown to induce attentional shifts. The size of this gaze shift is of the order of 0.1-0.2° visual angle, meaning fixation was maintained on the intended location, just slightly skewed.

Liu et al. (2022) extended this research using the same visual working memory task as van Ede et al. (2019) (figure 3). Liu et al. showed that more microsaccades were made towards the cued memory-item when internal spatial attention was shifted. Microsaccades are defined as the tiny eye movements used to keep a stable fixation, and therefore occur within 1° visual angle. The timeframe of this microsaccade bias is slightly different from the earlier found gaze bias: it occurs between 200 ms and 600 ms after the memory-cue. Interestingly, they did also find trials in which spatial attention was consistently shifted, where no corresponding shift in saccade direction was found. This implies that directional biases in microsaccades correlate with spatial attention, but are not necessary for spatial attention to manifest.
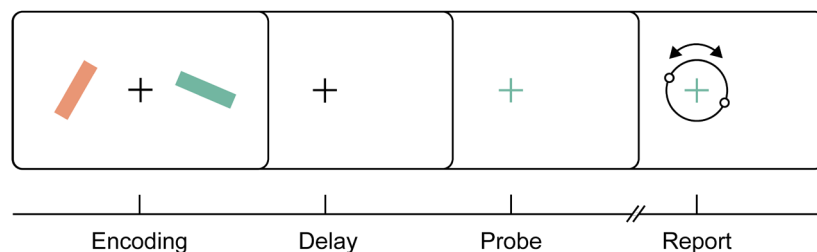

Figure 3: Task design of van Ede et al. (2019) and Liu et al. (2022). *Participants were instructed to memorise two coloured, tilted bars over a short delay, in order to reproduce the orientation of the probed item at the end of the delay. The probe was a lasting colour change of the central fixation cross, the colour of which determined of which memory item the orientation should be reproduced.*

Stimulus-driven internal attention?

To summarise: we know that goal-driven internal attention is possible and that it co-occurs with an ocular signature that is reflected in both gaze position and microsaccade direction. Is the same then also true for stimulus-driven internal selective attention?

We are not the first ones to ask this question, but it has not been studied very often yet. In a follow-up study by van Ede et al. (2020), they found participants were able to reproduce the orientation of the memory items with more accuracy if a colour-matching retrocue for that item was shown (see figure 4). This retrocue also evoked a bias in gaze position towards the cued item, reflecting that the cue induced an attentional shift towards the cued item. Crucially, even in the blocks where participants were informed that the retrocue was not predictive for which item would eventually be probed, the behavioural and gaze effects still occurred. This implies such an uninformative retrocue involuntarily and automatically draws attention to the colour-matching memory item. We call this an involuntary "attentional-capture effect". The occurrence of this effect would mean stimulus-driven internal attention is indeed possible.
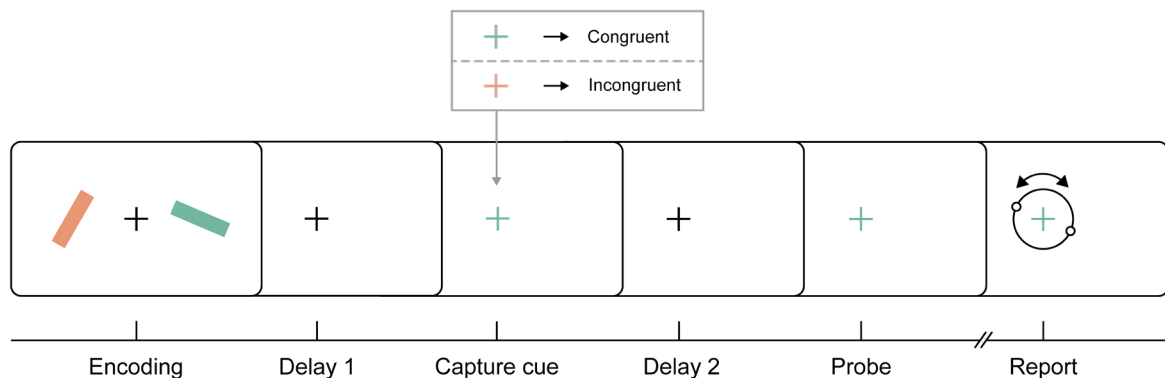

Figure 4: Task design of van Ede et al. (2020). *Participants were instructed to memorise two coloured, tilted bars over a short delay, in order to reproduce the orientation of the probed item at the end of the delay. The probe was a lasting colour change of the central fixation cross, the colour of which determined of which memory item the orientation should be reproduced. Halfway through the delay, a capture cue was shown in an attempt to elicit an involuntary attentional-capture effect.*

This attentional-capture effect occurs exactly within the intersection between visual working memory and attention: attention is used to select representations that only exist within visual working memory. When this selection occurs due to an external stimulus, as is the case in the experiment by van Ede et al. (2020), it is a clear example of internally directed selective attention, caused by an external source (see the bottom-right quadrant of figure 2).

However, in two thirds of the trial blocks in the experiment by van Ede et al. (2020), the colour-matching retrocue was 100% predictive for which item would be probed. It is therefore possible that these blocks trained participants to use the information from the retrocue, consequently making the retrocue too difficult to ignore in the blocks where the cue was uninformative. If this explanation of the involuntary capture-effect following an uninformative cue is correct, this experiment does not provide evidence for the existence of stimulus-driven internal attention. Another possibility is that the uninformative retrocue does induce an involuntary capture-effect brought on by stimulus-driven internal attention, but that the surrounding blocks of informative retrocues are a prerequisite for this effect to occur.

This brings us to the point of contention: (1) is a completely uninformative cue capable of and sufficient for creating an involuntary attentional-capture effect? And if so, (2) is this again reflected in an ocular signature consisting of a bias in gaze position and microsaccade direction? In the case that it is indeed stimulus-driven internal attention that creates the behavioural effect as seen in van Ede et al., one more question still remains: (3) is the behavioural effect that results from the attentional capture due to a benefit to the correctly cued memory item, a cost to the incorrectly cued memory item, or a combination of both?

In order to answer all three questions, the visual working memory task from van Ede et al. (2020) can be employed, after changing it in two significant ways: (1) use only an uninformative retrocue, a so-called "capture cue", in order to determine whether the blocks with informative cues serve as a prerequisite for the involuntary capture-effect occurring in the blocks with only an uninformative cue; (2) add a neutral condition to the capture cue, in which none of the original memory items are cued, in order to determine whether a cost or a benefit is the cause of the behavioural effect.

Based on the previous research we expect to find a behavioural attentional-capture effect, by observing less reproduction error and/or shorter decision times when the capture cue colour-matches the eventually probed item. We also expect that this behavioural effect is accompanied by both a bias in gaze position and microsaccade direction towards the cued memory item. Finally, we expect that the behavioural effect is caused by both a benefit and a cost. This would result in the behavioural effect being greatest in correctly cued items, followed by uncued items, and finally, being smallest in incorrectly cued items.

Methods

As explained in the introduction, our visual working memory task was very similar to that of van Ede et al. (2020), with three main exceptions: (1) our capture cue was always completely uninformative, unlike the original experiment in which the retrocue was informative two thirds of the time; (2) our capture cue also appeared in a neutral condition, in which neither of the two memory items were cued; and (3) our participant response has changed from a mouse-based input to a keyboard-based input, which created a two-alternative forced-choice response.

Two separate experiments were performed for this research. Both aimed to investigate stimulus-driven internal selective attention by using a behavioural experiment in combination with eye-tracking. The methods and materials used for both experiments were identical, except when explicitly stated otherwise.

Sample sizes

Sample sizes for both main experiments (experiment 1 and 2) were set to 25 prior to data collection, based on previous studies from our laboratory with similar tasks and outcome measures. However, the data from experiment 1 still looked very inconsistent after 16 participants, 64% of the final sample, and it was therefore decided to stop data collection prematurely. Considering that the results of experiment 1 differed greatly from previous, and very similar, experiments, we decided to repeat the experiment with only a slight change in one of the key parameters. This yielded experiment 2, which was performed in its entirety.

Participants and ethics

This research was approved by The Scientific and Ethical Review Board (VCWE) of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam. All participants were healthy human volunteers who provided written informed consent prior to participation, and received compensation of €10 per hour. All participants had normal or corrected-to-normal vision, were not colourblind and had no diagnosed ADHD, ADD or schizophrenia, but other diagnoses were possible and were not recorded.

16 participants performed experiment 1, of which 10 identified as female and 14 were right-handed. The participants of experiment 1 had an average age of 24.3 ± 4.2 (M ± SD), with a total age range of 18 to 35 years old. 25 participants performed experiment 2, of which 17 identified as female and 1 identified as non-binary. All 25 participants were right-handed. The participants of experiment 2 had an average age 23.2 ± 3.1 (M ± SD), with a total age range of 18 to 31 years old. No participants from either experiment were removed from the final dataset. This decision was based on two factors: all participants had adequate eye-tracking data as determined through visual inspection, and all behavioural performances fell within the expected bounds (M ± 3 SD).

Task design

The visual working memory task was developed in Python 3.8.16 using the Psychopy package. In this task participants were instructed to memorise two coloured, tilted bars over a 2.5-second delay (figure 5). After a colour change of the central fixation cross (the memory probe), participants were prompted to reproduce the orientation of the colour-matching memory item as precisely as possible. A single trial consisted of six separate frames: (1) the stimuli frame, shown for 250 ms, (2) the first delay, a fixation cross, shown for 750 ms, (3) the capture cue frame, shown for 250 ms, (4) the second delay, a fixation cross, shown for 1250 ms, (5) the probe cue frame, shown until participants started to respond, and finally: (6) the report itself, which could last for a maximum of 1000 ms. Performance was displayed at the end of each trial and trials were separated by a fixation cross shown for 500 ms. In order to avoid any sensory-driven attentional shifts, both the probe cue and the response dial were displayed centrally.

The probe cue was always a fixation cross that colour-matched the target memory item, i.e. the memory item of which the orientation should be reported. Our key manipulation was that the capture cue could either (1) also colour-match the target memory item, (2) colour-match the non-target memory item or (3) match neither memory items by being a different, third colour. This created three trial conditions, respectively: congruent, incongruent and neutral.
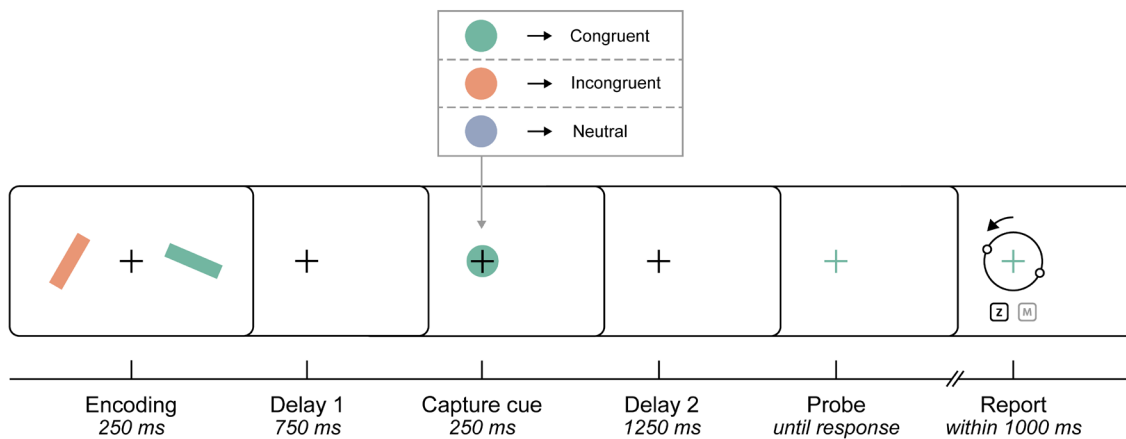
Figure 5: Task schematic. *Participants were instructed to memorise two coloured, tilted bars over a 2.5-second delay, in order to reproduce the orientation of the probed item at the end of the delay. The probe was a lasting colour change of the central fixation cross, the colour of which determined of which memory item the orientation should be reproduced. Halfway through the delay, a capture cue was shown in an attempt to elicit an involuntary attentional-capture effect.*

The onset of the probe cue indicated it was possible to start the response: participants were always required to reproduce the orientation of the target memory item, by using the keyboard to move the response dial in the correct direction. The response dial appeared at response initiation (i.e., a keyboard press) at a 0°, upright, angle, and kept turning until response termination, with the final position of the response dial being registered as the responded orientation. Pressing 'm' made the response dial move clockwise, while pressing 'z' made the response dial move anti-clockwise. The response dial moved at a speed of 90°/s for the duration the keyboard press was sustained, until a maximum of exactly one second, after which the response was automatically terminated. It was not possible to release the response key to pause the response or change direction. Participants were instructed to make the response dial match up as precisely as possible with the desired orientation. This means participants had to decide which response key to press before initiating a response.

Procedure and materials

Participants performed the visual working memory task while seated in a closed cubicle with dimmed lights, in order to eliminate all possible distractions as much as possible. Before starting the experiment, participants practiced trials of all conditions until both experimenter and participant agreed the objective was clear and performance was adequate.

The experimental task consisted of 16 blocks of 48 trials each, leading to a total of 768 trials per participant and lasting for ~90 minutes including breaks. Trial conditions were pseudo-randomly generated to ensure every condition occurred in exactly 1/3 of the trials in each block. Target locations were also pseudo-randomly generated to ensure the target appeared in each possible location in exactly 1/2 of the trials in each block. After each block participants could take a self-paced break, in which they were instructed not to move their head. After 8 blocks participants could take a self-paced break in which they were allowed to get up and move around.

During the task, participants sat ~70 cm away from the monitor on which the task was displayed (24-inch; resolution of 1920 x 1080 pixels; refresh rate of 239 Hz), resulting in ~45 pixels per degree visual angle. The memory items were bars of 4° visual angle in height by 0.6° visual angle in width, and were presented at a 6° visual angle distance from the centre of the screen. Four colours were randomly used for the memory items and capture cue in all trials: red (RGB: 255, 153, 172), yellow (RGB: 245, 226, 163), green (RGB: 168, 240, 209) and blue (RGB: 153, 206, 255). Four colours were used for the experiment so the neutral colour was not automatically set after two colours were randomly chosen for the target and non-target memory items. The bars had an (independently chosen) random orientation between -85 and 85 degrees, except they could not be oriented between -5 and 5 degrees. This created a total of 160 possible positions for each bar.

Differences between experiment 1 and 2

Experiments 1 and 2 were completely identical in task design and procedure, with the exception of the shape of the capture cue. In experiment 1 the capture cue was an empty square surrounding the central fixation cross, while in experiment 2 the capture cue was a filled circle presented behind the central fixation cross. See figure 6 for a side-by-side comparison.

Recruitment for experiments 1 and 2 was performed independently and recruitment for experiment 2 only started once experiment 1 was concluded, but participants could participate in both. Although, only one participant actually participated in both experiments.
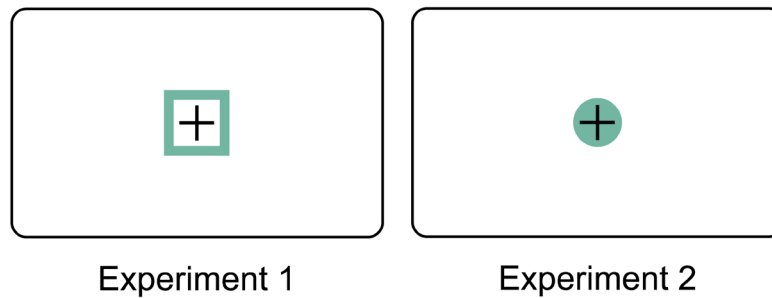
Figure 6: comparison of capture cues for experiment 1 and 2. *The colours that were used in both experiments are identical; the colour shown here serves only as an illustration.*

Performance analysis

The primary statistical analyses compared different conditions within each participant (i.e., within-subjects design). Three main measures were extracted from the behavioural data: decision time, reproduction error and (in)correct key usage. All behavioural analyses were done in MATLAB R2023a.

Decision times were defined as the time between probe onset and the onset of a keyboard response, this explicitly does not include the response time itself. The response time is not an informative measure in this experiment, since the constant angular speed and inability to change directions of the response dial make the response time fully dependent on the angle that has to be reproduced.

Reproduction errors were defined as the absolute difference between the probed memory item's orientation and the reported orientation, each as defined in the almost-semicircular 160° space.

Incorrect key usage was evaluated only for those trials where both memory items were angled in opposite directions, meaning one was positioned at an angle > 0° and one < 0°. Only in those cases would reporting their individual orientations require a different keyboard response. This analysis is interesting since it reflects the original confusion between both memory items, without showing the ability of the participant to adapt and keep the reproduction error as small as possible in the cases where the participant realises that they used the wrong response key.

In addition, a 3-component mixture model was fitted per participant to evaluate swap errors. This model decomposes a participant's responses into normal and uniform components, with normal components reflecting target and non-target responses and uniform components reflecting the "guess frequency". A measure for the precision of the normal components is also produced. It is however prudent to note that this is a relatively simplistic approach to evaluating participants' responses, and it is known that the non-target parameter has a tendency to underestimate the swap frequency (Bays, 2016; Taylor & Bays, 2020).

Eye tracking: acquisition and analysis

The eye tracker (Eyelink 1000 Plus by SR Research) was positioned ~15 cm in front of the monitor, on the same table the participants were sitting at. Horizontal and vertical gaze positions of the participant's right eye were continuously sampled at a rate of 1000 Hz. The eye tracker was calibrated and validated before the experiment using the built-in gaze calibration module in which participants are asked to look at a small white dot that is repositioned on the screen, whenever a stable fixation is registered at the current position. The HV9 calibration model was used, in which nine calibration points on the screen are used in a random order: top, middle and bottom for left, middle and right (SR Research Ltd., 2013; *Which Calibration Model Should I Use?*, 2020). The eye tracker was always re-calibrated halfway through the experiment (after 8 blocks), and could additionally be re-calibrated in each break, if the signal was deemed of too poor quality.

Following acquisition, eye tracker datafiles were converted from their original Eyelink Data Format (.edf) to an ASCII text file (.asc), and read into MATLAB R2023a using Fieldtrip. Custom code was used to detect blinks and turn the signal for 100 ms before and after each blink to NaN values. Our eye tracking analyses focus on two main measures: gaze towardness as a function of time, and toward-vs.-away saccade rate as a function of time.

To calculate gaze towardness, first all trials in which the gaze deviation at any time during the trial was larger than 50 pixels were removed, since in these trials fixation was not constantly maintained. Then a baseline correction was applied, using a period of 250 ms immediately prior to capture cue onset as baseline. Gaze towardness is then calculated by taking the difference between the horizontal gaze position in trials with a target on the left and trials with a target on the right, divided by 2. Therefore, gaze towardness reflects how much participants are looking towards the *target*, even though the target is not known to the participant yet before the onset of the probe cue. This allows for the usage of the same frame of reference for all trial conditions: during neutral trials, none of the original memory items are ever cued, but the target item is always probed at the end of a trial. This method was adapted from (van Ede et al., 2019, 2020).

Saccades were extracted from the data using a custom function which detects gaze shifts based on the horizontal gaze velocity (which is equal to the derivative of horizontal gaze position) exceeding a certain threshold, in this case 5 x the median rate of change. This method was also used by Liu et al. (2022). Any gaze shift between 0° and 1000° visual angle were used in the final analysis. Saccades could be classified as toward or away, with respect to whether or not the horizontal direction was toward the target memory item or not. The toward-vs.-away saccade rate is then defined as the difference between the rate of saccades made towards and away from the target memory item.

Statistical analyses

All behavioural data were compared over the three different conditions (congruent, neutral and incongruent) using a one-way repeated-measures ANOVA per dependent variable. Partial effect-sizes of condition were also calculated by excluding intersubject variance from the η^2 calculation. Any significant ANOVAs were evaluated post-hoc using pairwise paired t-tests, with Bonferroni-corrected α-values. Any comparisons between the two experiments were done using independent t-tests.

All eye-tracking data were statistically evaluated using cluster-based permutation analyses, which have the main benefit of avoiding the multiple-comparisons problem. Such a permutation analysis evaluates the entire time-course under a single permutation distribution of the largest cluster. We used the default cluster settings in FieldTrip and ran 1000 permutations per evaluation.

Finally, Pearson's correlation coefficients were calculated to relate the toward-vs.-away saccade rate to decision times. This was done by calculating effect sizes per participant for each of these variables. The decision time effect size is simply the difference in decision times between congruent and incongruent trials. Saccade rate effect sizes were calculated by averaging the difference in toward-vs.-away saccade rate between congruent and incongruent trials, over a period of 200 - 600 ms following capture cue onset. This window was picked a priori, based on the work by Liu et al. (2022).

Results of experiment 1

We aimed to investigate whether a completely uninformative cue proved sufficient to induce an involuntary capture effect, and whether this effect constitutes a benefit to the cued memory item, or a cost to the uncued item. To this end, we collected decision times, reproduction error and eye movements of 16 participants during a visual working memory task. In the following section we first analyse behavioural performance and investigate whether congruency between capture cue and probe cue affects participants' performances. To reiterate, three conditions of congruency were used in this experiment: congruent, neutral and incongruent.

Behavioural results

Figure 7 shows memory performance on experiment 1 as a function of trial condition. Figures 7A and 7B respectively show average decision time and reproduction error. To eliminate intersubject variability in average performance, all values were mean-subtracted within participants, as shown in figure 7C and 7D. Average decision times seem to be lower for congruent trials, in comparison to both neutral and incongruent trials, but these differences are not significant ($F_{(2,15)}$ = 1.145, p = 0.332, partial η^2=0.0709, where the partial η^2 refers to all variance explained by condition, after excluding intersubject variance). The same is true for the average reproduction error ($F_{(2,15)}$ = 0.397, p = 0.676, partial η^2=0.0258).

Since the orientations of both memory items were always generated completely independently, approximately 50% of the time both memory items were tilted in the same direction. This means in ~50% of the trials, reproducing the orientation of the probed memory item requires the same key-press as reproducing the orientation of the unprobed memory item. By considering the data of only those trials where the memory items were oriented in opposite directions, the proportion of incorrect key-presses can be calculated (figure 8). This proportion of incorrect key-presses is expected to be higher in the incongruent condition, based on the assumption that participants will mistakenly try to report the orientation of the capture-cue-matching item. This difference was not found ($F_{(2,15)}$ = 0.870, p = 0.429, partial η^2=0.0548).
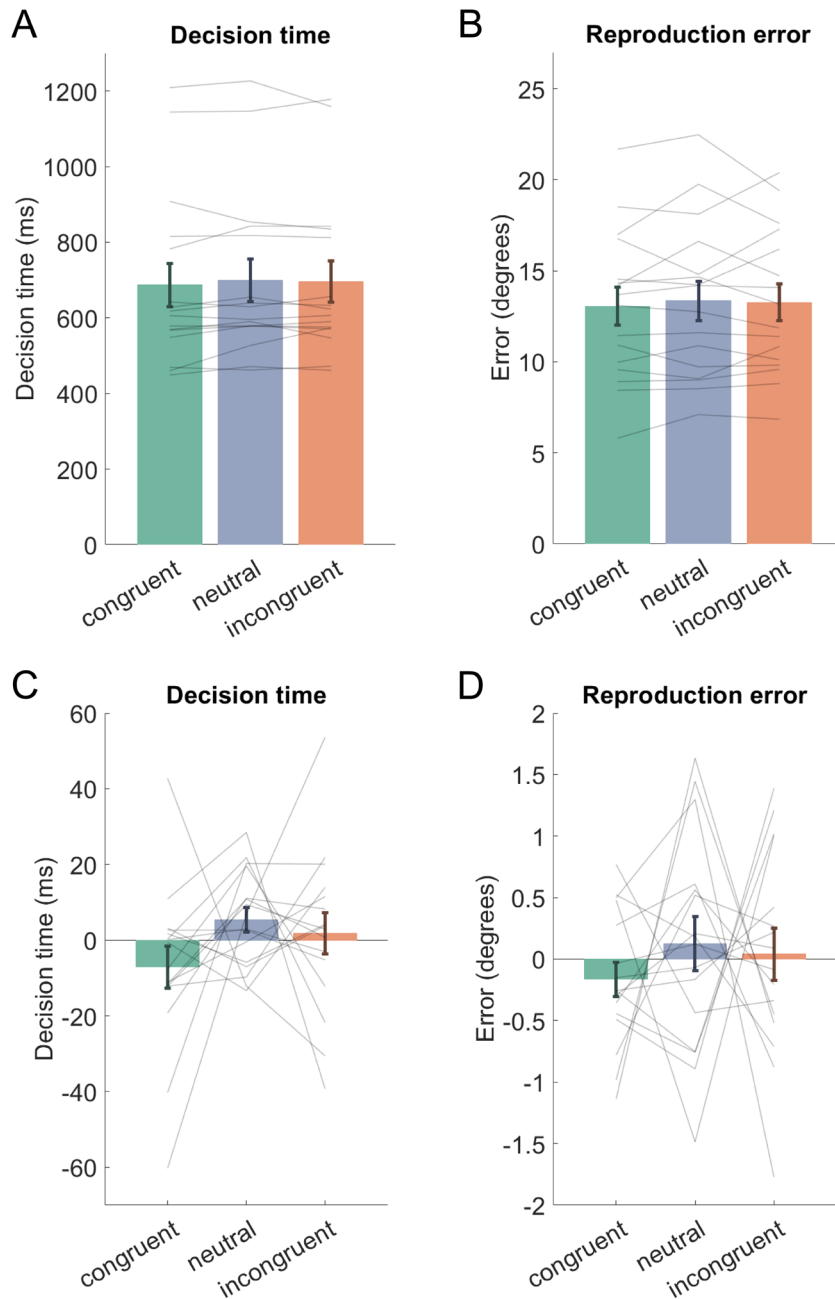
***Figure 7: behavioural performance in experiment 1 as a function of congruency between capture cue and probe cue.** Bars in A and B indicate averages, bars in C and D indicate mean-subtracted averages, with error bars always indicating standard error across participants. Grey lines show individual participants' performances. (A) and (C) Decision time in ms, no significant differences. (B) and (D) Reproduction error in degrees, no significant differences.*
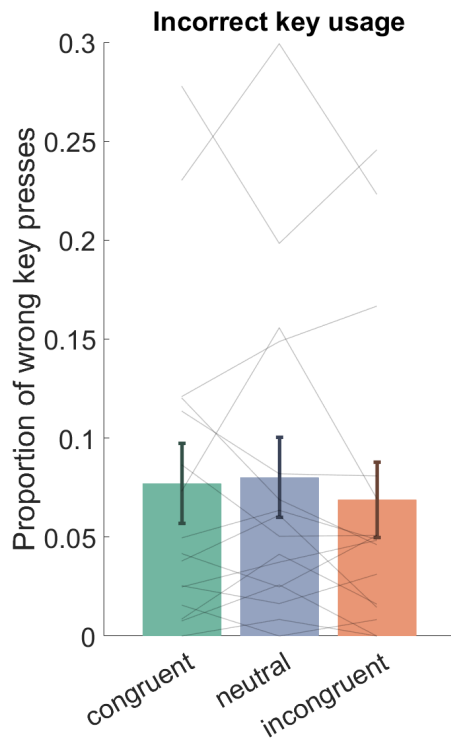
Figure 8: incorrect key usage in experiment 1 as a function of congruency between capture cue and probe cue. *Bars indicate the average proportion of trials in which the wrong response key was used, with error bars indicating standard error across participants. Grey lines show individual participants' performances. No significant differences were found.*

Participants' responses can be further evaluated for swap errors using a mixture model, as first described in Bays et al. (2009). This descriptive model attempts to describe report performance by representing it as a probabilistic mixture of three types of responses: target-responses, non-target responses, and uniform responses. Target responses refer to responses that correctly attempt to recreate the relevant feature of a cued item, with some variability. Non-target responses refer to responses that mistakenly attempt to recreate the relevant feature of an uncued item, with the same variability as before. Uniform responses refer to randomly generated responses, that are unrelated to both cued and uncued memory items.

Creating a mixture model per participant produces four measures of performance for each participant: the precision of their responses (k) and the estimated probabilities of target, non-target and uniform responses (which sum to 1). Figure 9 shows the average model parameters of all participants. If participants are sufficiently distracted by the capture cue, it is expected that the probability of non-target responses increases in incongruent trials, but this is not the case (figure 9C; $F_{(2,15)} = 1.574$, $p = 0.224$, partial $\eta^2 = 0.095$). All other mixture model parameters also do not differ between conditions (respectively: precision, p(target), p(uniform)): $F_{(2,15)} = 0.821$, $p = 0.450$, partial $\eta^2 = 0.0519$;
$F_{(2,15)} = 0.153$, $p = 0.859$, partial $\eta^2 = 0.0101$; $F_{(2,15)} = 0.738$, $p = 0.487$, partial $\eta^2 = 0.0469$.
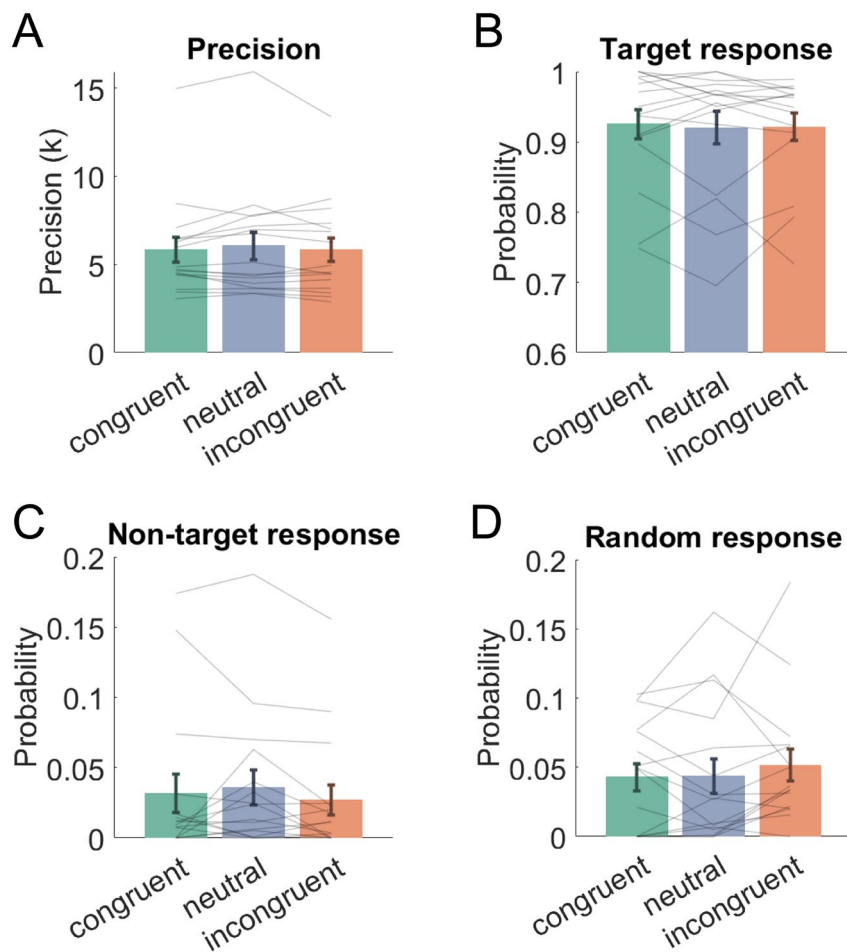
Figure 9: mixture model parameters in experiment 1 as a function of congruency between capture cue and probe cue. *Bars indicate averages, with error bars indicating standard error across participants. Grey lines show individual participants' performances. (A) Precision of the response curve, no significant differences. (B) Estimated probability of target responses, no significant differences. (C) Estimated probability of non-target responses, no significant differences. (D) Estimated probability of uniform (i.e. random) responses, no significant differences.*

Eye-tracking results

As mentioned in the introduction, attentional capture can elicit an ocular signature, which can be reliably measured with eye-tracking. One of these ocular signatures is the bias of a participant's gaze towards the original location of the memory item that is currently active in their mind. To investigate whether a spatial bias in gaze occurs following the capture cue in experiment 1, figure 10A shows the average gaze towardness to the target memory item throughout a single trial. The average gaze towardness is obtained by averaging across participants. Gaze towardness is shown separately for congruent, neutral and incongruent trials. The shaded areas reflect the standard error.

To better visualise the effect of the capture cue on gaze towardness, the gaze towardness during incongruent trials can be subtracted from the gaze towardness during congruent trials to show the effect of the capture cue on gaze position. Gaze towardness is always defined with regard to the eventual target memory item. If participants tend to shift their gaze towards the cued memory item, this will create an increase of gaze towardness in congruent trials, but a decrease in gaze towardness in incongruent trials. This is because in incongruent trials the capture cue does not cue the eventual target item. Note that the gaze towardness is always the average gaze towardness across all participants. The data resulting from this operation is shown in figure 10B. Based on previous studies, the gaze towardness is expected to differ significantly between conditions between 400-1000 ms after capture cue onset (van Ede et al., 2020). To evaluate whether this gaze effect differs significantly from zero, clusters were detected between the onset of the capture cue and the onset of the probe cue (0 – 1500 ms). This showed the gaze effect differed significantly from zero from 770 – 1500 ms after capture cue onset ($p = 0.0040$).

Rather than studying the overall gaze position of participants throughout a trial, saccades can also be used to investigate attentional capture. Both the size and direction of saccades are interesting in that respect. Figure 11A shows the average saccade rate in the direction toward the target memory item, for congruent, neutral, and incongruent trials separately. Shaded areas reflect standard error.

Again, the average saccade rate towards the *target* memory item during incongruent trials can be subtracted from congruent trials to investigate the presence of a saccade bias towards the *cued* memory item following the onset of the capture cue. Figure 11B shows this saccade rate effect. Based on previous studies, an increase of the saccade rate effect would be present between 200 and 600 ms after capture cue onset (Liu et al., 2022). To evaluate whether this effect ever differed significantly from zero, clusters were detected between the onset of the capture cue and the onset of the probe cue (0 – 1500 ms), but none were found.
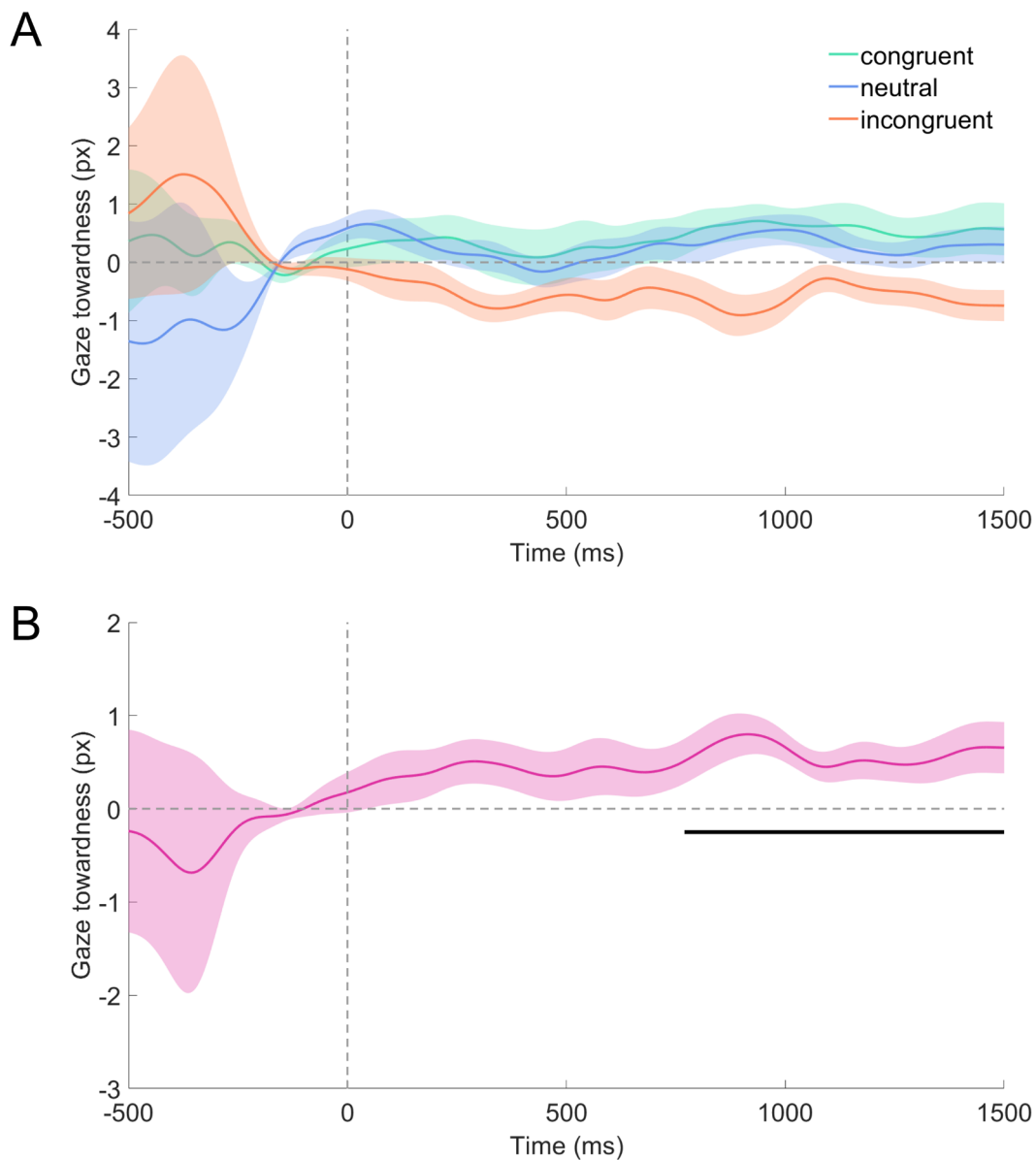
Figure 10: horizontal gaze towardness in pixels over time for experiment 1. *Coloured lines show average horizontal gaze towardness in any particular condition, with shaded areas reflecting standard error across participants. Timepoint 0 indicates onset of the capture cue. (A) Overlay of horizontal gaze towardness in pixels over time for congruent, neutral and incongruent conditions. (B) Difference in horizontal gaze towardness between congruent and incongruent conditions. A gaze towardness above zero means at that timepoint more towardness to the target memory item was observed in the congruent condition versus the incongruent condition. Statistical testing was performed on the 0 – 1500 ms time-course and significantly non-zero time-courses are indicated with a horizontal black line.*
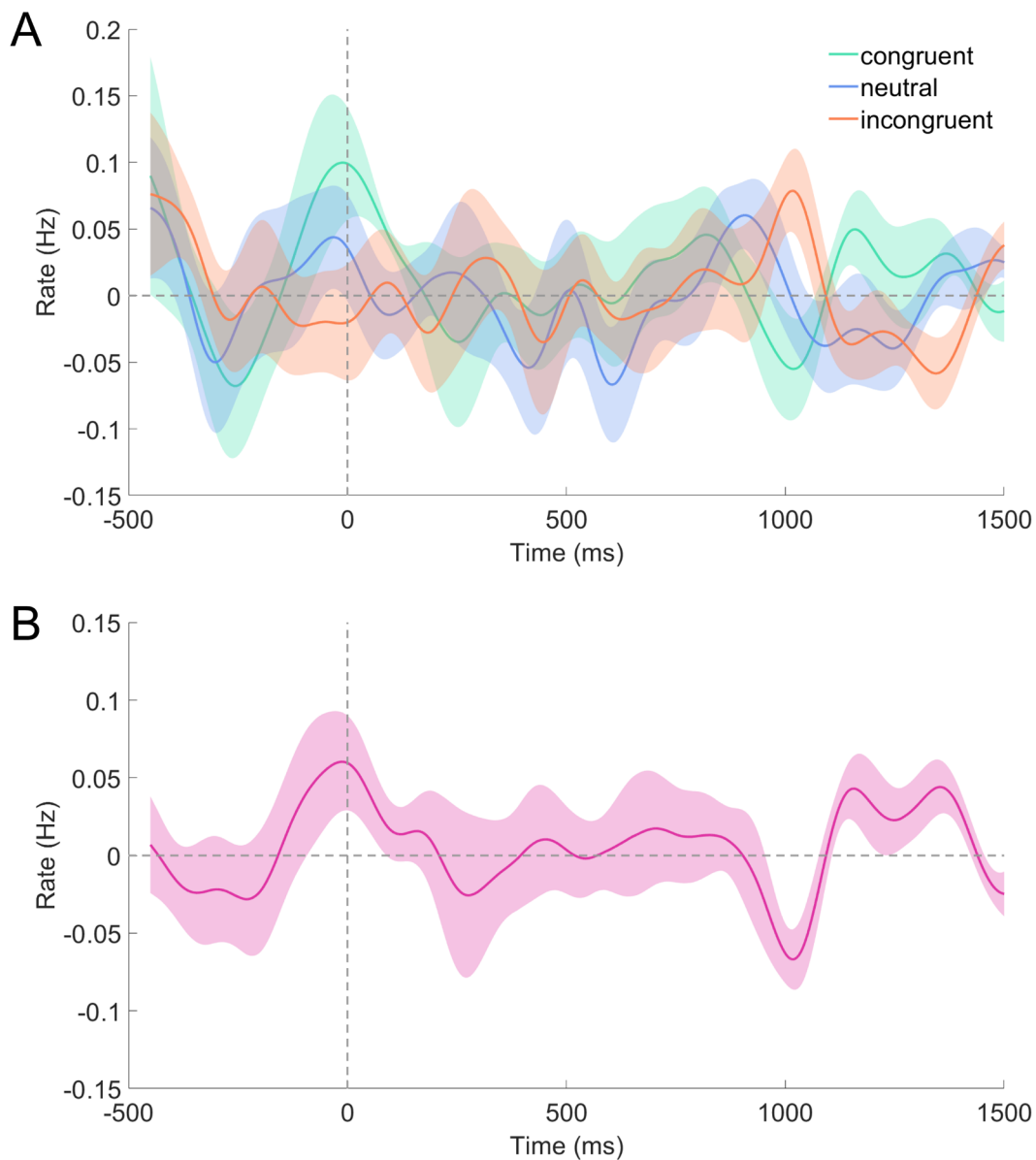
Figure 11: saccade rate towards vs. away over time for experiment 1. *Coloured lines show the average rate of saccades made towards the target memory item in any particular condition, with shaded areas reflecting standard error across participants. Timepoint 0 indicates onset of the capture cue. (A) Overlay of saccade rate toward vs. away over time for congruent, neutral and incongruent conditions. (B) Difference in toward-vs.-away saccade rate between congruent and incongruent conditions. A rate above zero means more saccades were observed towards the target memory item in the congruent condition versus the incongruent condition at that timepoint. Statistical testing was performed on the 0 – 1500 ms time-course, but no significantly non-zero time-courses were found.*

While the previous plots provide information on the direction of saccades, they do not reflect the size of the saccades that were made. Figure 12 shows the average rate of saccades made towards the *cued* memory item in both incongruent and congruent trials, along with their size in degrees visual angle. Both figures show the majority of saccades were smaller than 1° visual angle, therefore showing that any present ocular effect would be driven by microsaccades.
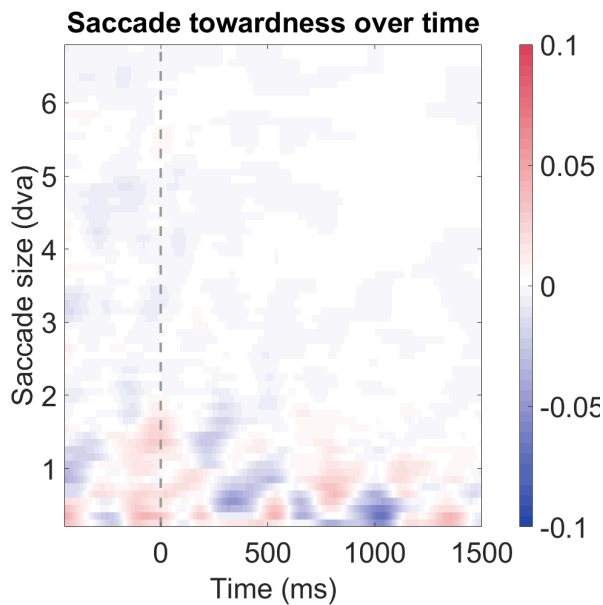

Figure 12: difference in toward-vs.-away saccade rate between congruent and incongruent conditions from experiment 1 along with saccade size. *Saccade sizes for the difference in saccade toward-vs.-away rate between congruent trials and incongruent trials, with saccade rate expressed in colour. Red coloured clusters indicate more saccades were made towards the target memory item in congruent conditions versus incongruent conditions at that timepoint, while blue coloured clusters indicate the opposite.*

Summary of results

Experiment 1 produced no significant behavioural capture effect. Conversely, a bias was found in the gaze towardness in the expected direction following capture cue onset, but this effect occurred relatively late compared to the expected timeframe. In addition, it was not corroborated by the saccade data, which did not show any significant bias. Due to this lack of consistent results, it was decided to abort the current experiment in order to re-do the experiment with a redesigned capture cue. We opted to change the capture cue to something more similar to what was used in previous studies, which is also displayed more centrally than the capture cue used in experiment 1. The hope is that the second version of the capture cue has a better chance of inducing an involuntary capture effect.

Results of experiment 2

The current experiment is a reproduction of experiment 1, except the visual working memory task contains a modified capture cue. The current experiment is again aimed to investigate whether a completely uninformative cue is able to elicit an involuntary capture effect, and whether this effect constitutes a benefit to the cued memory item, or a cost to the uncued item. Therefore we collected decision times, reproduction error and eye movements of 25 participants, during the modified visual working memory task. In the following section we first investigate the behavioural performance and consider whether congruency between capture cue and probe cue affects participants' performances. The same three conditions of congruency are present in this experiment as before.

Behavioural results

Figure 13 shows memory performance on experiment 2 as a function of trial condition. Figures 13A and 13B respectively show average decision time and reproduction error. To eliminate intersubject variability in performances, all values were mean-subtracted within participants, as shown in figure 13C and 13D. Average decision times differed significantly between conditions ($F_{(2,24)} = 11.506$, $p = 8.275e\text{-}05$, partial $\eta^2=0.324$). This difference was evaluated post-hoc using pairwise t-tests, which showed the decision time on congruent trials was significantly lower than both neutral trials ($t_{(24)} = -3.857$, $p = 7.564e\text{-}04$) and incongruent trials ($t_{(24)} = -3.632$, $p = 0.0013$), when evaluated using $\alpha = 0.0125$, due to the Bonferroni correction. Neutral trials and incongruent trials did not differ significantly on decision time ($t_{(24)} = 1.345$, $p = 0.191$). The reproduction error shows no significant difference between the different conditions ($F_{(2,24)} = 0.531$, $p = 0.591$, partial $\eta^2=0.0217$).

The proportion of incorrect key presses was again evaluated for all trials where the memory items were oriented in opposite directions (figure 14). This proportion of incorrect key-presses is expected to be higher in the incongruent condition, based on the assumption that participants will mistakenly try to report the orientation of the capture-cue-matching item. While this trend seems present, there is no significant difference between the conditions ($F_{(2,24)} = 1.242$, $p = 0.298$, partial $\eta^2=0.0492$).
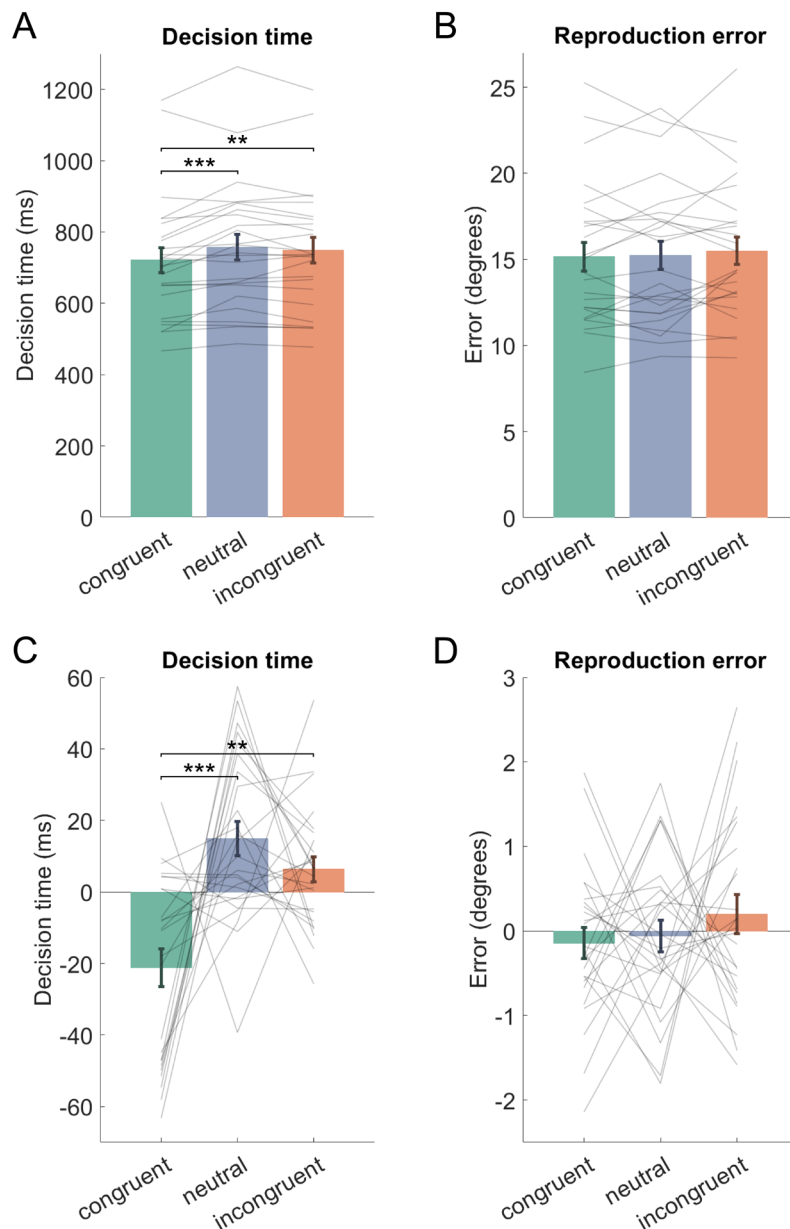
Figure 13: behavioural performance in experiment 2 as a function of congruency between capture cue and probe cue. *Bars in A and B indicate averages, bars in C and D indicate mean-subtracted averages, with error bars always indicating standard error across participants. Grey lines show individual participants' performances. (A) and (C) Decision time in ms; average decision times in the congruent condition differed significantly from both neutral and incongruent conditions. Significance levels are indicated by asterisks: two asterisks indicate the p-value has a value between 0.01 and 0.001, while three asterisks indicate that the p-value has a value smaller than 0.001. (B) and (D) Reproduction error in degrees, no significant differences.*
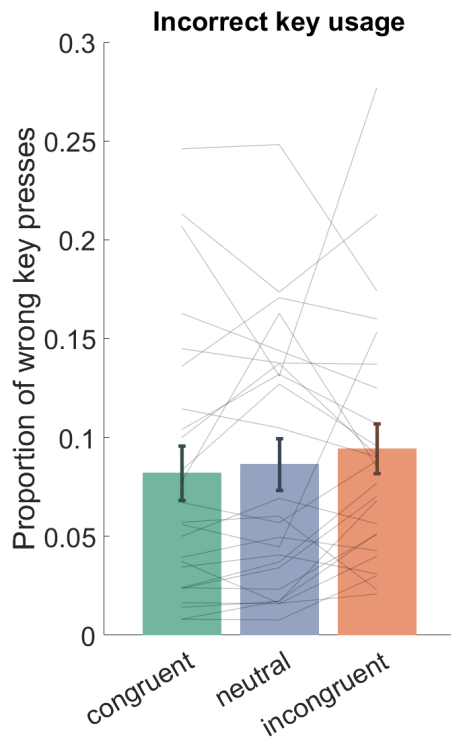
Incorrect key usage

Figure 14: incorrect key usage in experiment 2 as a function of congruency between capture cue and probe cue. Bars indicate the average proportion of trials in which the wrong response key was used, with error bars indicating standard error across participants. Grey lines show individual participants' performances. No significant differences were found.

Subsequently, a mixture model (Bays et al., 2009) was created per participant, producing four measures of performance for each participant: the precision of their responses (k) and the estimated probabilities of target, non-target and uniform responses (which sum to 1). Figure 15 shows the average model parameters of all participants. If participants are sufficiently distracted by the capture cue, it is expected that the probability of non-target responses increases in incongruent trials (figure 15C). This does seem to be the case, but the difference is insignificant ($F_{(2,24)} = 0.260$, $p = 0.772$, partial $\eta^2=0.0107$). All other mixture model parameters also do not differ between conditions (respectively: precision, p(target), p(uniform)): $F_{(2,24)} = 1.215$, $p = 0.306$, partial $\eta^2=0.0482$;
$F_{(2,24)} = 1.365$, $p = 0.265$, partial $\eta^2=0.0538$; $F_{(2,24)} = 1.026$, $p = 0.366$, partial $\eta^2=0.0410$.
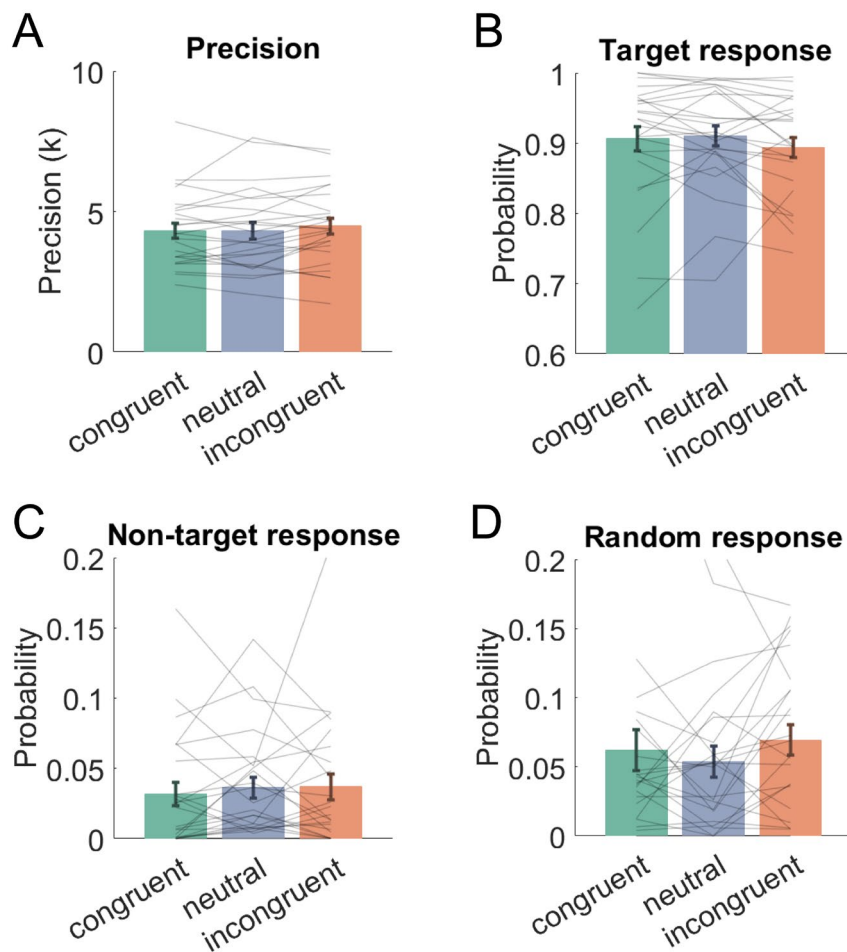
Figure 15: mixture model parameters in experiment 2 as a function of congruency between capture cue and probe cue. *Bars indicate averages, with error bars indicating standard error across participants. Grey lines show individual participants' performances. (A) Precision of the response curve, no significant differences. (B) Estimated probability of target responses, no significant differences. (C) Estimated probability of non-target responses, no significant differences. (D) Estimated probability of uniform (i.e. random) responses, no significant differences.*

Eye-tracking results

To investigate whether a gaze bias occurred following the onset of the capture cue in experiment 2, figure 16A shows the average gaze towardness to the target memory item throughout a single trial. The average gaze towardness is obtained by averaging across participants. Gaze towardness is shown separately for congruent, neutral and incongruent trials. The shaded areas reflect the standard error.

To better visualise the effect of the capture cue on gaze towardness, the average gaze towardness during incongruent trials can be subtracted from the average gaze towardness during congruent trials to show the effect of the capture cue on gaze position. In accordance with experiment 1, gaze towardness is always defined in respect to the target memory item. Therefore, an increase of gaze towardness is expected in congruent trials, but a decrease in gaze towardness is expected in incongruent trials, provided that participants tend to shift their gaze towards the cued memory item. Note that the gaze towardness is always the average gaze towardness across all participants. The data resulting from this operation is shown in figure 16B. Based on previous studies, the gaze towardness is expected to differ significantly between conditions between 400-1000 ms after capture cue onset (van Ede et al., 2020). To evaluate this, clusters were detected between the onset of the capture cue and the onset of the probe cue (0 – 1500 ms), and it was found that the gaze effect differs significantly from zero (p = 0.0270) between 923 ms and 1297 ms after capture cue onset.

Saccades were again calculated to show the effect of the capture cue on the direction and rate of saccades, for congruent, neutral, and incongruent trials separately. Figure 17A shows the rate of saccades made towards the target memory item following the capture cue, with shaded areas reflecting standard error. Notably, the difference between toward-saccade rate between congruent and incongruent trials is much larger during the 200-600 ms timeframe following the onset of the capture cue than it was in experiment 1.

Again, the average saccade rate towards the *target* memory item during incongruent trials can be subtracted from congruent trials to investigate the presence of a saccade bias towards the *cued* memory item following the onset of the capture cue. Based on previous studies, an increase of this saccade rate effect would be present between 200 and 600 ms after capture cue onset (Liu et al., 2022). Figure 17B shows this saccade bias effect. To evaluate whether this effect ever differed significantly from zero, clusters were detected between the onset of the capture cue and the onset of the probe cue (0 – 1500 ms), but none were found. The saccade bias is therefore never significant, but it does present in the expected pattern: following capture cue onset, the saccade rate towards the memory item increases up until ~600 ms post capture cue onset. After which it drops below 0, indicating saccades are being made in the opposite direction, presumably to return to the centre of the fixation cross.
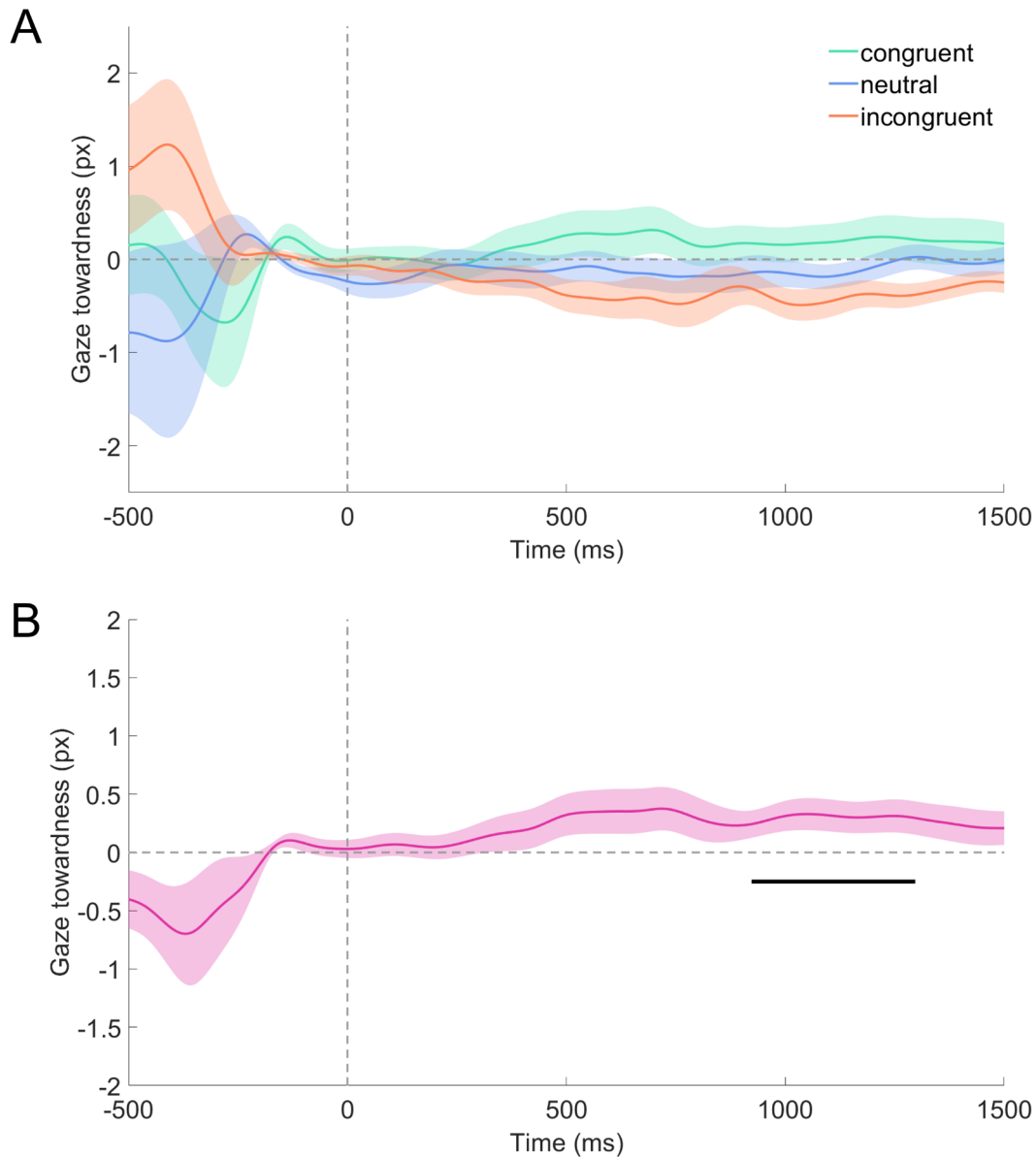
Figure 16: horizontal gaze towardness in pixels over time for experiment 2. *Coloured lines show average horizontal gaze towardness in any particular condition, with shaded areas reflecting standard error across participants. Timepoint 0 indicates onset of the capture cue. (A) Overlay of horizontal gaze towardness in pixels over time for congruent, neutral and incongruent conditions. (B) Difference in horizontal gaze towardness between congruent and incongruent conditions. A gaze towardness above zero means at that timepoint more towardness to the target memory item was observed in the congruent condition versus the incongruent condition. Statistical testing was performed on the 0 – 1500 ms time-course and significantly non-zero time-courses are indicated with a horizontal black line.*
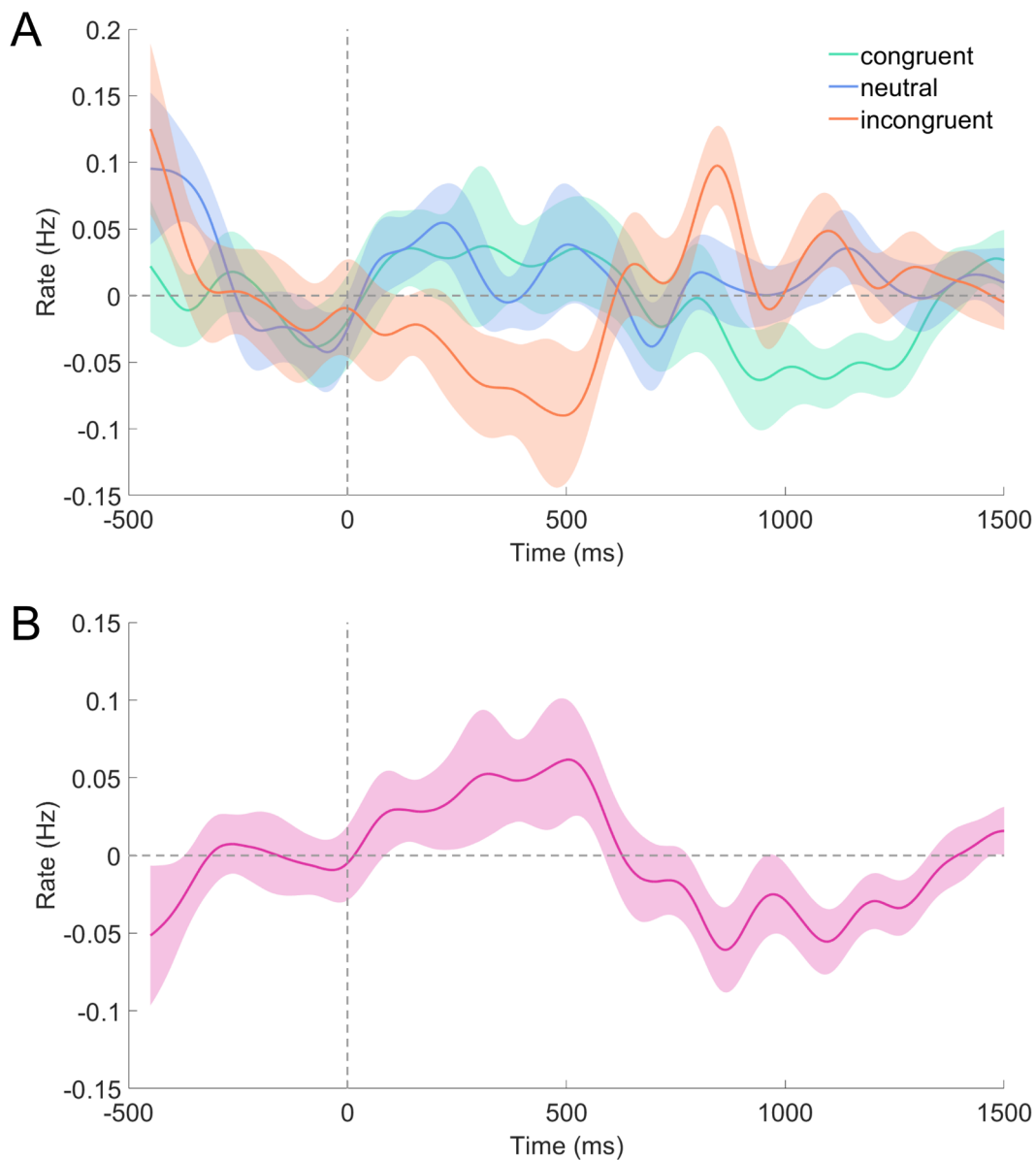
Figure 17: saccade rate towards vs. away over time for experiment 2. *Coloured lines show the average rate of saccades made towards the target memory item in any particular condition, with shaded areas reflecting standard error across participants. Timepoint 0 indicates onset of the capture cue. (A) Overlay of saccade rate toward vs. away over time for congruent, neutral and incongruent conditions. (B) Difference in toward-vs.-away saccade rate between congruent and incongruent conditions. A rate above zero means more saccades were observed towards the target memory item in the congruent condition versus the incongruent condition at that timepoint. Statistical testing was performed on the 0 – 1500 ms time-course, but no significantly non-zero time-courses were found.*

While the previous plots provide information on the direction of saccades, they do not reflect the size of the saccades that were made. Figure 18 shows the average rate of saccades made towards the *cued* memory item in both incongruent and congruent trials, along with their size in degrees visual angle. Both figures show the majority of saccades were smaller than 1° visual angle, therefore showing that any present ocular effect is driven by microsaccades.
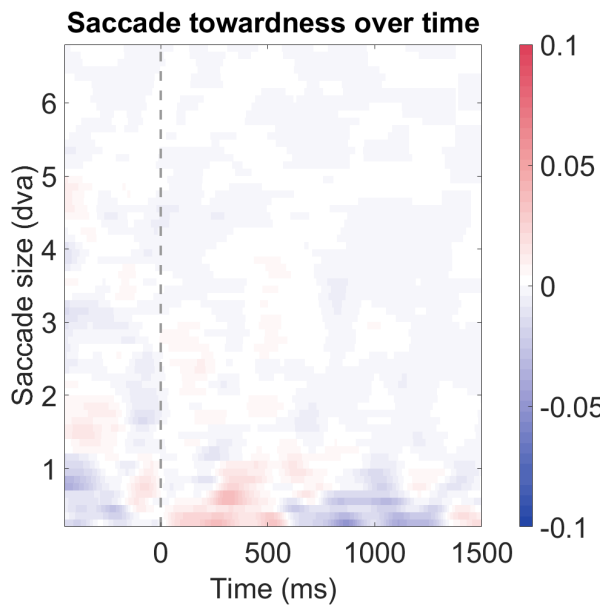

Figure 18: difference in toward-vs.-away saccade rate between congruent and incongruent conditions from experiment 2 along with saccade size. Saccade sizes for the difference in saccade toward-vs.-away rate between congruent trials and incongruent trials, with saccade rate expressed in colour. Red coloured clusters indicate more saccades were made towards the target memory item in congruent conditions versus incongruent conditions at that timepoint, while blue coloured clusters indicate the opposite.

Relationship between ocular bias and behavioural effect

It is unexpected that a behavioural capture effect could be present, without any gaze or saccade bias to reflect this also. Further investigation of the link between ocular bias and behavioural effect is therefore necessary. In order to do this, both a behavioural and an ocular effect size were extracted from the data. As the capture cue induced only a behavioural effect on decision time, the average difference per participant between the decision time on incongruent versus congruent trials was taken as behavioural effect size. The saccade rate change most followed the expected pattern, and was therefore used for the ocular effect size, rather than the gaze towardness data. To create a robust measure of ocular effect size, the difference in saccade rates towards the target memory item between incongruent and congruent trials was calculated (congruent – incongruent, meaning a larger effect size indicates more saccades towards the *cued* memory item). This difference (which was already shown in figure 17B), was then averaged over the time period of 200 - 600 ms following the capture cue, as earlier studies find the largest effect within this timeframe (Liu et al., 2022).

Figure 19A shows the correlation between saccade rate effect and decision time effect within participants. This correlation follows the expected direction, but not significantly (r = 0.39, p = 0.054). The median decision time effect in experiment 2 is 19.40 ms; this can be used to split the group into two groups of approximately equal size. All participants with a decision time effect larger than the median are highlighted in magenta (n = 12) in figure 19B, all other participants have a decision time effect at or below the median of 19.40 (n = 13).
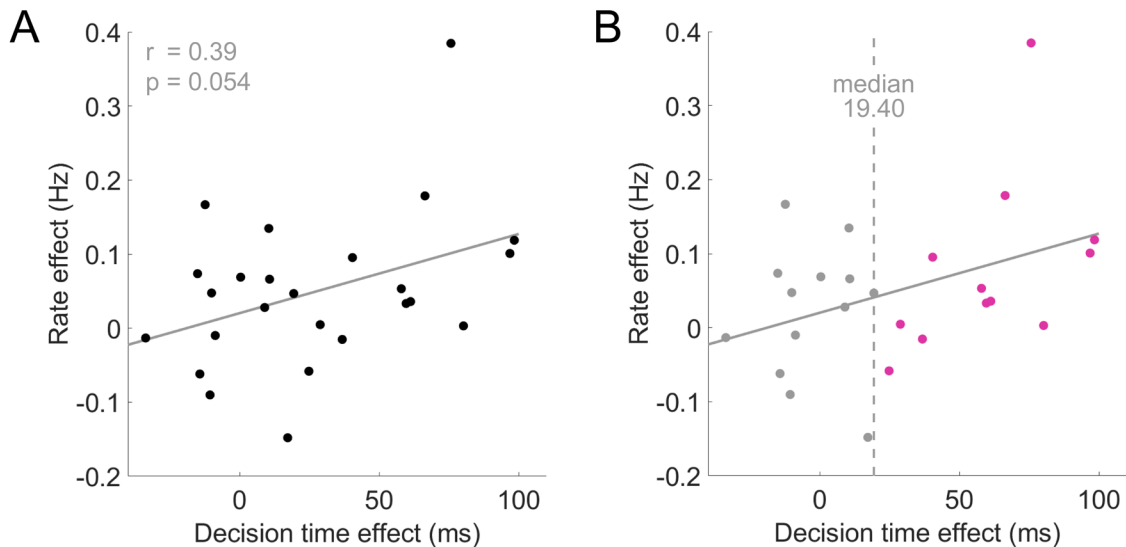

Figure 19: correlation across participants between saccade rate effect and decision time effect in experiment 2. *Saccade rate effect size is created by taking the difference in toward-vs.-away saccade rate following a congruent vs. incongruent capture cue. Decision time effect size is created by taking the difference in average decision time following a congruent vs. incongruent capture cue. Grey line shows least squares regression line. (A) All participants from experiment 2. Pearson's r and corresponding p-value are provided in the upper-left corner. (B) All participants from experiment 2, with a dashed-line at a decision time effect of 19.40, to separate an above-median decision time effect group and a below/at-median decision time effect group. The above-median group is highlighted in magenta.*

Since a trend is present in the aforementioned correlation, it is interesting to compare the ocular data of both groups. Figure 20 shows this comparison (for a larger version, see figure A1). It now seems the group with a larger decision time effect shows a much clearer saccade rate bias in both the congruent and incongruent conditions, between 200 and 600 ms. To investigate this, the saccade rate of incongruent trials was subtracted from congruent trials, which shows this difference is significant in the large decision time effect group from 377 - 531 ms after the capture cue (p=0.0380), and from 846 - 1165 ms after the capture cue (p=0.0030). The other group saccade rate contains no significant clusters.
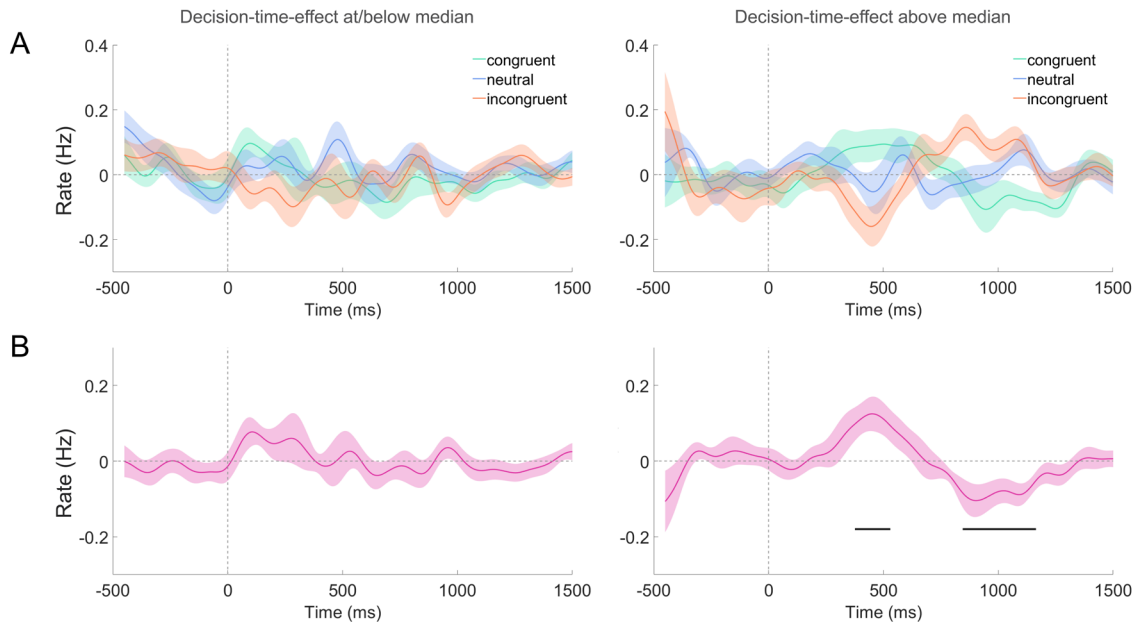
Figure 20: comparison of toward-vs.-away saccade rate over time for above-median and below/at-median decision time effect groups from experiment 2. Coloured lines show the average rate of saccades made towards the target memory item in any particular condition, with shaded areas reflecting standard error across participants. Timepoint 0 indicates onset of the capture cue. (A) Overlay of saccade rate toward vs. away over time for congruent, neutral and incongruent conditions, for the below/at-median (left) and above-median (right) decision-time-effect groups. (B) Difference in toward-vs.-away saccade rate between congruent and incongruent conditions, for the below/at-median (left) and above-median (right) decision-time-effect groups. A rate above zero means more saccades were observed towards the target memory item in the congruent condition versus the incongruent condition at that timepoint. Statistical testing was performed on the 0 – 1500 ms time-courses and significantly non-zero time-courses are indicated with a horizontal black line.

Summary of results

Experiment 2 produced a significant behavioural capture effect on decision times, but this capture effect was not fully reflected in the ocular data: gaze towardness seems biased between 900 - 1300 ms after capture cue onset, but saccade biases are not significantly present at group-level. However, if the data from experiment 2 is split by the median decision time effect into two groups, we see the group with a larger decision time effect shows a significant saccade rate bias. This bias is significant within the expected time-period, but also well after this period, which can be explained as the logical consequence of returning the gaze back to the original position. This explanation is supported by the fact that this second saccade rate bias is observed in the opposite direction of the initial one.

Combined data of experiment 1 and 2

While experiment 1 did not show a significant behavioural effect on decision time, the decision times in experiment 1 did follow the exact same pattern as in experiment 2. Additionally, experiment 2 showed an interesting relationship between decision time effect and saccade rate effect. Based on the similarities in the data between experiment 1 and 2, it was decided to also investigate whether there was any correlation between behavioural effect and ocular effect in experiment 1 (figure 21). This correlation follows the expected direction, but again not significantly so ($r = 0.38$, $p = 0.143$). However, correlation analyses are notoriously sensitive to the amount of available data. It was therefore decided to also perform the correlation analysis with the pooled data of both experiments. Since the experiments only differ in the shape of the used capture cue, this correlation is at least not influenced by third factors, like timing, response manner or task instruction. The resulting analysis shows a significant correlation in the expected direction ($r = 0.42$, $p = 0.006$), which indicates that participants with a larger decision time effect, generally also show a larger saccade rate effect.

To further investigate the differences between experiment 1 and 2, the individual decision time and saccade rate effects were compared (respectively, figure 22A and figure 22B). The average decision time effect in experiment 1 was 8.89 ± 42.28 (M ± SD), as compared to 27.62 ± 38.02 in experiment 2. This difference was not significant ($t_{(39)} = -1.4730$, $p = 0.1488$). A similar pattern is found when comparing saccade rate effects following the capture cue: the average saccade rate effect in experiment 1 was -0.0071 ± 0.107 (M ± SD), as compared to 0.0497 ± 0.104 in experiment 2. This difference was again not significant ($t_{(39)} = -1.6895$, $p = 0.0991$).
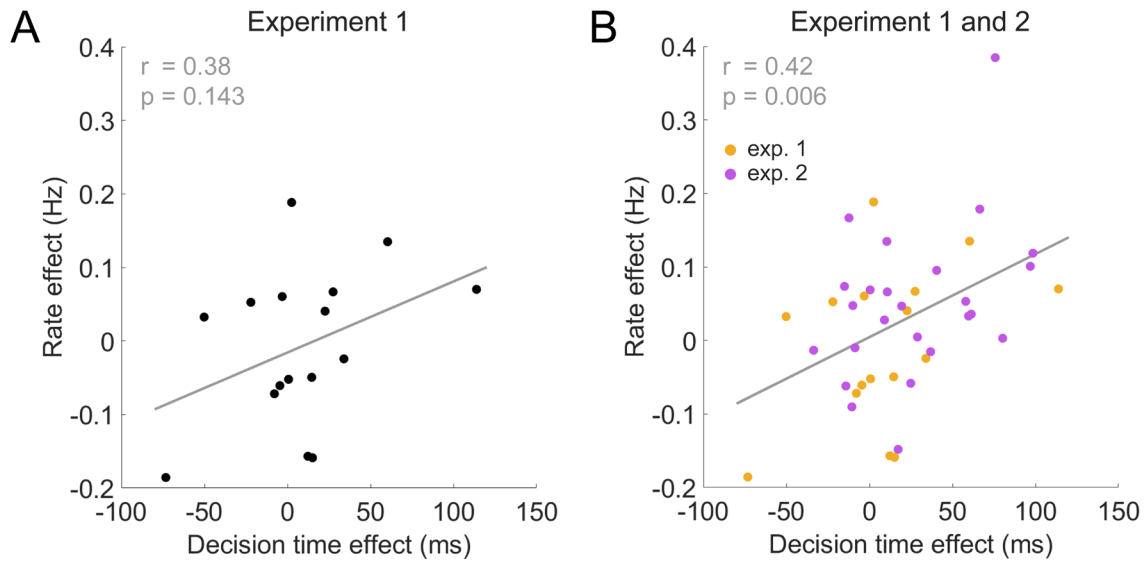
Figure 21: correlation across participants between saccade rate effect and decision time effect, for experiment 1 and both experiments combined. *Saccade rate effect size is created by taking the difference in toward-vs.-away saccade rate following a congruent vs. incongruent capture cue. Decision time effect size is created by taking the difference in average decision time following a congruent vs. incongruent capture cue. Grey lines show least squares regression line. Pearson's r and corresponding p-value are provided in upper-left corners. (A) All participants from experiment 1. (B) All participants from experiment 1 and 2 combined, with participants from experiment 1 marked in yellow and participants from experiment 2 marked in purple.*
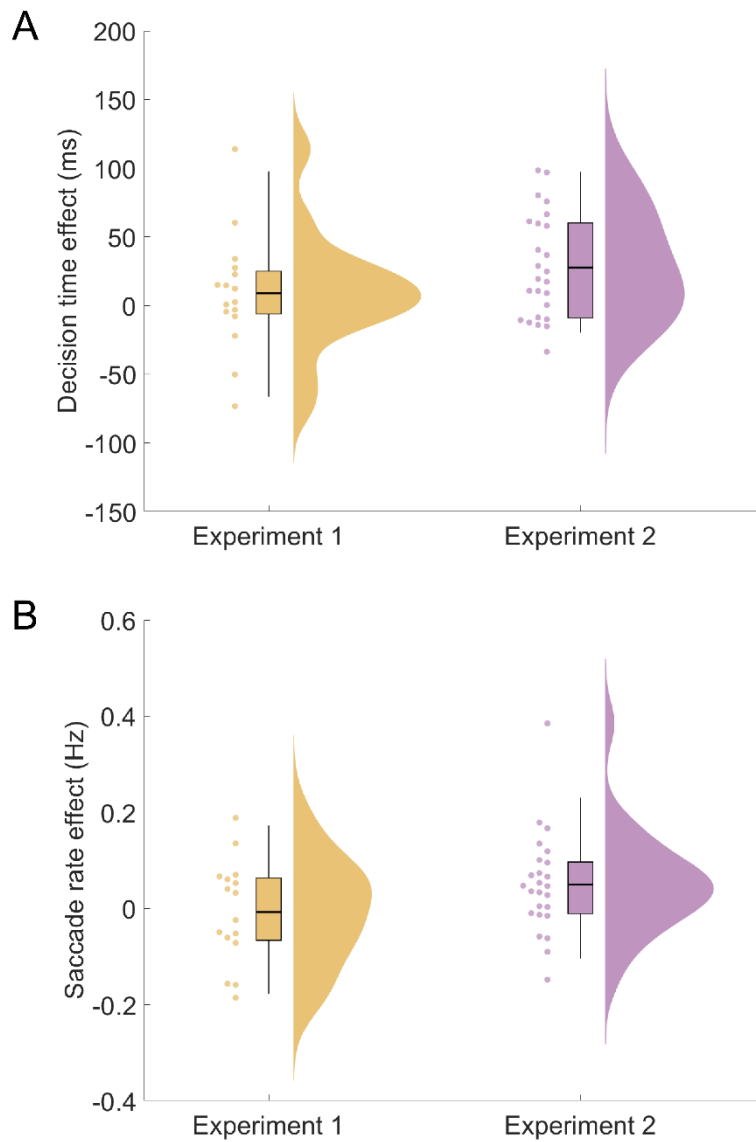
Figure 22: comparison of key data from experiment 1 and 2. *Dots show individual data points, coloured box shows 25th to 75th percentile, vertical black lines denote 5th to 95th percentile, horizontal black lines indicate mean values. Coloured half-violin plots show the probability density estimate for each group, as based on a normal kernel function. One hundred equispaced points are used to create the probability density estimate. (A) Comparison of decision time effect between experiment 1 and 2, no significant differences. (B) Comparison of saccade rate effect following the capture cue between experiment 1 and 2, no significant differences.*

Sanity check

The gaze and saccade data from both experiment 1 and 2 are quite noisy, and do not always show the expected effects. It is therefore important to test the validity of the acquired ocular data, as all previous conclusions rest on the assumptions that the current experimental set-up is capable of eliciting and registering the expected ocular effects. The best way to do this is by calculating the gaze effect and saccade effect following the *probe* cue, since it is clear attentional selection must take place at that moment in time. To do this, clusters were detected within the 1000 ms timeframe following the probe cue at 1500 ms.

Figure 23A shows the gaze towardness throughout an entire trial, with the probe cue being shown at 1500 ms (for a larger version, see figure A2). The coloured horizontal bars represent when the gaze towardness in each individual condition differs significantly from zero. To re-iterate: based on previous research this gaze bias is expected approximately 400 – 1000 ms post onset of the probe cue (van Ede et al., 2020). A gaze bias is therefore expected between 1900 and 2500 ms. In experiment 1 the congruent condition created a significant gaze-bias between 1823 – 2500 ms ($p < 0.001$); the neutral condition between 1775 – 2500 ($p < 0.001$); and the incongruent condition between 1500 – 1776 ms ($p = 0.0140$), 1896 – 2082 ms ($p = 0.0350$), and 2465 – 2500 ($p = 0.0020$). In experiment 2 the congruent condition created a significant gaze-bias between 1800 – 2500 ms ($p < 0.001$); the neutral condition between 1806 – 2500 ms ($p < 0.001$); and the incongruent condition between 1500 – 1736 ms ($p = 0.0430$) and 1838 – 2500 ms ($p < 0.001$).

Figure 23B shows the saccade rate towards the target memory item throughout an entire trial (for a larger version, see figure A2). The coloured horizontal bars represent when the saccade rate in each individual condition differs significantly from zero. To re-iterate: based on previous research this saccade bias is expected approximately 200 – 600 ms post onset of the probe cue (Liu et al., 2022). A saccade bias is therefore expected between 1700 and 2100 ms. Throughout experiment 1 the congruent condition created a significant saccade bias between 1672 – 2102 ms ($p < 0.001$) and 2350 – 2839 ms ($p = 0.0030$); the neutral condition between 1733 – 2093 ms ($p = 0.0020$) and 2298 – 2527 ms ($p = 0.0120$); and the incongruent condition between 1697 – 2052 ms ($p < 0.001$). During experiment 2 the congruent condition created a significant saccade bias between 1696 – 2072 ms ($p < 0.001$) and 2394 – 2500 ms ($p < 0.001$); the neutral condition between 1675 – 2060 ms ($p < 0.001$) and 2339 – 2500 ms ($p < 0.001$); and the incongruent condition between 1692 - 2088 ms ($p < 0.001$).
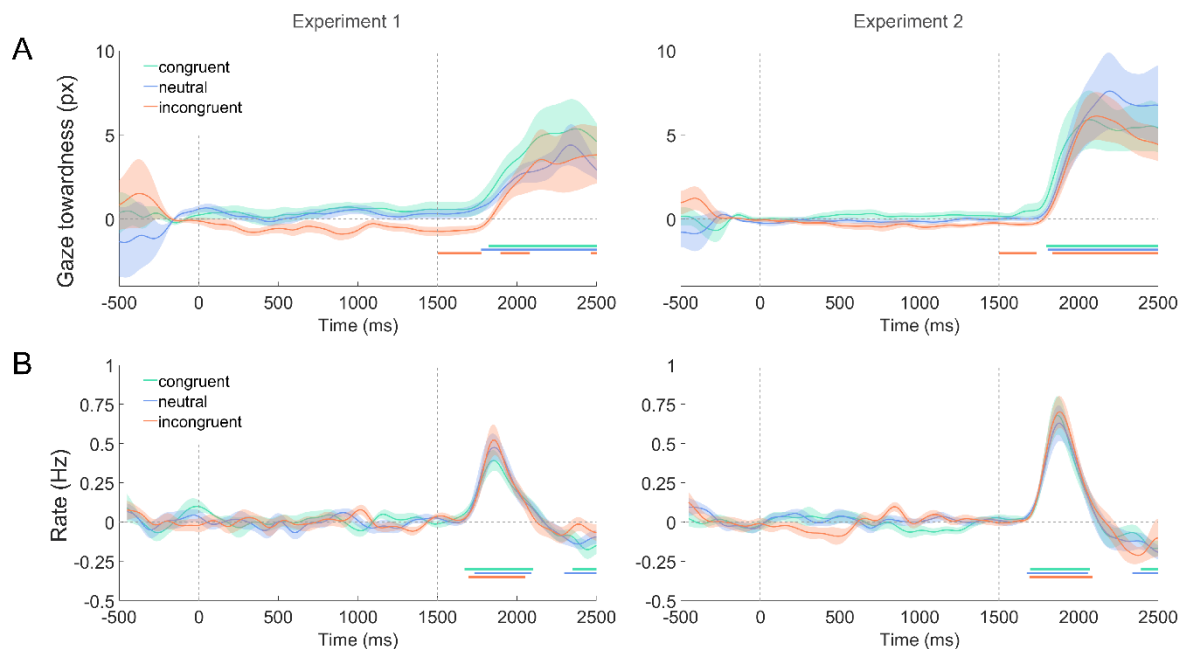

Figure 23: gaze towardness and toward-vs.-away saccade rate over time in congruent, neutral and incongruent trials for experiment 1 and 2, separately. *Timepoint 0 indicates onset of the capture cue. Onset of the probe cue is shown with a dashed line at 1500 ms. Statistical testing was performed on the 1500 – 2500 ms time-course. All significantly non-zero time-courses are visualised with correspondingly-coloured horizontal bars. (A) Coloured lines show average horizontal gaze towardness in the congruent, neutral and incongruent conditions, with shaded areas reflecting standard error across participants. Shown for experiment 1 (left) and 2 (right) separately. (B) Coloured lines show the average rate of saccades made towards the target memory item in the congruent, neutral and incongruent conditions, with shaded areas reflecting standard error across participants. Shown for experiment 1 (left) and 2 (right) separately.*

Figure 24 shows the toward-vs.-away saccade rate at any timepoint during all trials, along with their size in degrees visual angle. Figure 24A shows this for experiment 1, while figure 24B shows the same for experiment 2. Both figures show the majority of saccades following the probe cue (at 1500 ms) were smaller than 1° visual angle, and are therefore characterised as microsaccades. Especially in experiment 2, larger saccades were also made, but almost none went as far as the original location of the memory items (6° visual angle). Both figures show the same pattern in saccade direction: following the probe cue more saccades are directed towards the target memory item, and after ~ 600 ms saccades are made in the opposite direction, presumably to return to the centre of the fixation cross.
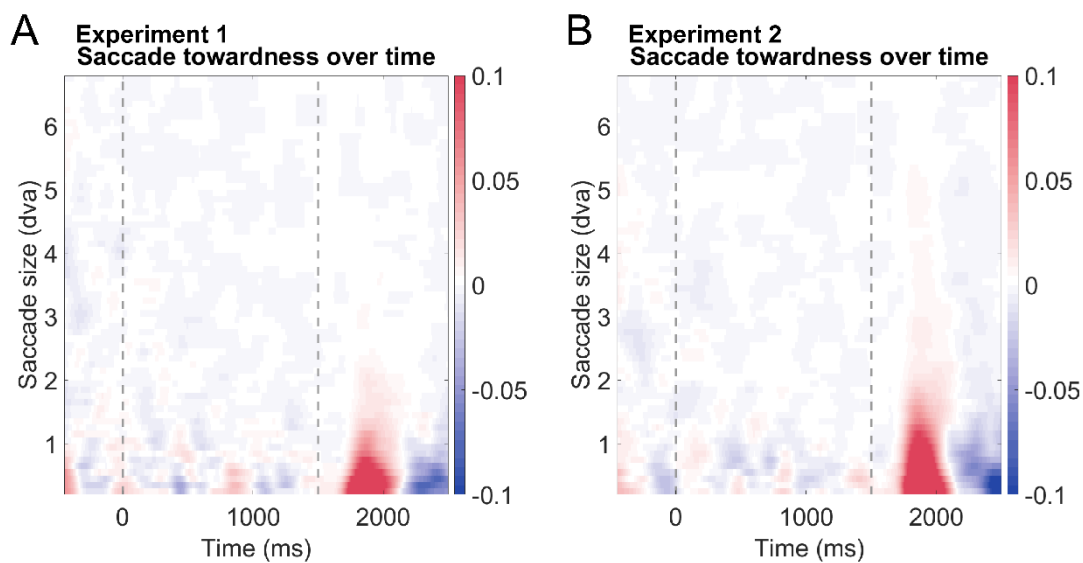

Figure 24: difference in toward-vs.-away saccade rate averaged over all trials per experiment along with saccade size. *Saccade sizes for the toward-vs.-away saccade rate over all trials with saccade rate expressed in colour. Red coloured clusters indicate more saccades were made towards the target memory item than away from it at that timepoint, while blue coloured clusters indicate the opposite. (A) Data from experiment 1. (B) Data from experiment 2.*

Summary of sanity check

Based on both the gaze towardness bias and the saccade rate bias it can be concluded that the ocular data is a robust reflection of attentional selection in both experiments. Both effects also occurred largely within the timeframes that were expected based on previous research. Finally, the saccade bias effect was mainly driven by microsaccades, which is also completely in line with earlier findings.

Discussion

The current study investigated whether a completely uninformative cue is capable of and sufficient for creating an involuntary attentional-capture effect. The study additionally explored whether this effect is reflected in an ocular signature consisting of a bias in gaze position and microsaccade direction, as predicted by previous research. Finally, the study also investigated whether this effect is due to a benefit to the cued memory item, a cost to the uncued memory item, or a combination of both.

Conclusion

In summary, experiment 1 showed a small gaze bias outside of the expected timeframe that was not accompanied by any behavioural effect or saccade bias. Experiment 2 showed a significant behavioural effect (on decision time) at group level, as well as a small gaze bias outside of the expected timeframe, but no saccade effect at group-level. However, a median split of decision time effect on the data from experiment 2 showed a significant saccade towardness effect for the above-median group. This saccade towardness effect also correlated significantly with the decision time effect, indicating a relationship between microsaccade direction and (involuntary) attentional capture.

Concerning the cost-vs.-benefit question, almost all eye-tracking data showed the neutral condition was most often between the congruent and incongruent conditions, indicating that a neutral capture cue simply has no effect on gaze position or saccade direction. Furthermore, the decision times in experiment 2 showed a significant difference between the congruent and neutral trials, and between congruent and incongruent trials, but not between neutral and incongruent trials. This indicates an attentional benefit when memory items are correctly cued, with no cost when memory items are incorrectly cued.

To conclude, it seems a completely uninformative capture cue is capable of and sufficient for creating an involuntary attentional-capture effect within a visual working memory task. This was also reflected in an ocular signature consisting of a small gaze bias on group-level, although this did not occur within the expected timeframe. More interestingly, a significant bias in microsaccade direction was also observed (within the expected timeframe), but not in all participants, and this is therefore not true at a group-level. Finally, it seems the behavioural effect is due to a benefit for cued items, at no cost to uncued items.

Comparison between experiments 1 and 2

Two separate experiments were performed to reach these conclusions. When comparing results between the two current studies, two points are worth discussing: (1) only experiment 2 induced a behavioural effect through the capture cue; (2) the attentional shift following the probe cue seemed more intense in experiment 2 in comparison to experiment 1.

The first finding seems to indicate that the capture cue in experiment 2 simply captured the attention better than the capture cue in experiment 1. While this is theoretically a possibility, it also raises the question of which aspects of the capture cue would be responsible for this. After all, the capture cue was changed in many ways from experiment 1 to 2: it was more centrally displayed, had a smaller size and a different shape. Our current data offer no possible answer to this question. Our tentative hypothesis would be that the centrality of the capture cue in experiment 2 is the aspect which most facilitates a stronger involuntary attentional capture, but confirmation of this hypothesis would require additional experiments.

Conversely, while the behavioural effects differed between experiment 1 and 2, simply comparing the decision time effect itself does not show any significant differences between the two experiments. The same is true for the saccade rate effect. This indicates that there was no difference in the effects found in both experiments, but confusingly, only experiment 2 shows a significant behavioural effect between the different conditions.

This seeming dichotomy between the behavioural effects in experiment 1 and 2 can be explained by the overall distributions of the experimental data. Experiment 1 consists of a much smaller population than experiment 2, but still has a larger spread of decision time effect than experiment 2. Consequently, the total spread of the distributions overlaps largely, and not enough participants in experiment 1 consistently show a behavioural effect. This both explains why the groups do not differ significantly from one another, as well as why experiment 1 does not show a significant behavioural effect between conditions.

The second difference between the experiments concerns the attentional shift following the probe cue. It seems this attentional capture was more intense in experiment 2 than in experiment 1: saccade bias, gaze bias and saccade size all seem larger following the probe cue in experiment 2 in comparison to experiment 1. (Note: no statistics were performed on these comparisons.) If this difference is truly present, it could indicate that the more intense attentional capture following the capture cue in experiment 2 is due to other factors than the capture cue itself.

Both the larger spread of data in experiment 1 and the seemingly smaller attentional capture following the probe cue, could be explained by multiple factors. One possible explanation is a difference in participant populations between both experiments, but these differences could also be the result of random chance. More interestingly, both findings could also be the direct result of a less effective capture cue in experiment 1. A less effective capture cue would create less consistent and less intense attentional captures immediately following the capture cue. This would explain the large spread of individual decision time effects found in experiment 1. This same lesser attentional capture could also mean a smaller attentional shift is required when finally selecting the target memory item after the probe cue is shown. This would explain the seemingly smaller attentional capture found post-probe in experiment 1.

Most importantly, the uncertainty of the data is quite high in the period following the probe cue, and the differences between experiment 1 and 2 were small. Therefore it seems unlikely one experiment truly elicited a smaller attentional capture following the probe cue than the other. Accordingly, it is also unlikely that this difference is an exhaustive explanation for the difference in effect following the capture cue between experiment 1 and 2. The most likely conclusion therefore remains that the capture cue in experiment 2 was more effective at involuntarily capturing attention. The lack of significant differences between experiment 1 and 2 concerning both effect sizes does remain interesting in combination with the previous conclusion, but the existing differences do follow the expected direction.

Comparison to van Ede et al. (2020) and Liu et al. (2022)
Because the current study is so closely based on previous work, from both van Ede et al. (2020) and Liu et al. (2022), it is pertinent to discuss how the current findings confirm or oppose this previous research.

When comparing our current results to those of van Ede et al. (2020) a few things stand out. First of all, van Ede et al. found a behavioural effect mainly on error, while we found it only on decision time. This is easily explained by one of the changes we made to the response dial: as mentioned in the methods section, the response input was changed from mouse-based to keyboard-based. This resulted in a forced-choice for the participant prior to their response onset, since changing the direction of the tilt was no longer possible after response initiation. This forces the participants to recall the orientation of the memory item before starting their response, therefore creating an effect on decision times. Conversely, in the original experiment by van Ede et al., the response dial could still be moved forwards and backwards after the first mouse movement. This better allows participants to respond the memory item's orientation as precisely as possible, therefore creating an effect on error. However, this combination of findings is noteworthy: it implies stimulus-driven attentional capture causes memory items to be both available more easily and recalled more accurately.

Secondly, the observed gaze bias in both current experiments was much smaller than the gaze bias observed by van Ede et al. (2020), and occurred later than the expected 400 to 1000 ms timeframe after cue onset. The observed gaze bias therefore does not fit the expected gaze effect very well. When examining the time course of the gaze bias more in-depth, the gaze position before timepoint zero stands out. This pre-cue gaze position always differs greatly between conditions, but the multiple trial conditions only start to differ from each other following the capture cue. It therefore seems unreasonable for gaze positions to differ between the conditions before capture cue onset.

One possible explanation for this difference is the baseline correction that was applied before calculating gaze position. This baseline correction is applied in an attempt to eliminate trial-to-trial differences in gaze starting position, but it uses the period of 250 ms prior to capture cue onset as baseline. This is a period during which no stimuli are shown on the screen, but the memory objects have been presented already. This could make it a suboptimal baseline period, since differences in gaze position could occur randomly. Using this period as a baseline could therefore result in incorrect gaze positions for the remainder of the trial, leading to inaccurate differences between conditions.

The microsaccade bias (when observed) did occur within the expected timeframe, but the rate bias was much smaller following the capture cue in the current experiment, than it was when following the probe cue in the original experiment by Liu et al. (2022). This does not necessarily indicate that the expected effect was not recorded; it could also mean the effect following the capture cue was simply weaker than following the probe cue. This explanation is quite plausible: a probe cue necessarily induces an attentional shift and selection of a memory item. By contrast, a capture cue only *possibly* induces an attentional shift, and does not require any selection of memory items. This explanation is supported by the fact that the microsaccade bias following the probe cue in both current experiments did correspond with the magnitude as found by Liu et al.

Another interesting aspect of the microsaccade bias is that it seems to reverse direction after approximately 650 ms. This reversal is easily explained: while participants first respond by making microsaccades toward the target memory item, the ocular system quickly realises that the gaze is no longer perfectly maintained on the point of fixation. Therefore this initial towardness bias is followed by an away bias, as microsaccades are made back towards the central fixation point. It is unknown whether this effect was also seen by Liu et al. (2022), since their microsaccade data is only displayed until 600 ms post-cue.

A short sanity check of the data was also described in the results section. Interestingly, both the gaze position bias and microsaccade direction bias following the probe cue fit very well with the earlier findings by van Ede et al. (2020) and Liu et al. (2022). Both biases occurred in the right timeframe and had the right order of magnitude. It therefore seems our experimental design was able to effectively induce and correctly identify attentional shifts, along with their corresponding ocular signature.

Future work

A final discussion point emerges after a closer inspection of the decision time results. These show that not all participants followed the same pattern. Remarkably, a large group of participants were indeed much slower in the neutral trials than in both congruent and incongruent trials, but there were also participants who did not follow this pattern at all. This suggests individual differences might play a significant role in a participant's capacity for involuntary attentional capture. The importance of these individual differences is further corroborated by the saccade bias in experiment 2, which was only found after a median split on decision time effect.

It would therefore be interesting to repeat this experiment with a much larger participant population. This would allow for the identification of multiple distinct groups, as based on a person's reaction to attentional capture cues. In the current study we used congruency of colour to elicit attentional shifts in people, but individual differences could also exist in the way people react to movement, location, timing, or other stimulus parameters. Furthermore, even if these additional experiments can identify distinct groups based on ocular signatures or behavioural biases, the question remains whether these individual differences are consistent over time. This question could be answered by performing a longitudinal study, in which the same participant population performs the same task on multiple occasions.

Further possibilities for future research into this topic could focus on the constraints of stimulus-driven internal attention, rather than simply proving stimulus-driven internal attention exists. The study of stimulus-driven internal attention is still in its relative infancy, and therefore many open questions remain. Questions that should be investigated include: how fast is it compared to other forms of attention? What is its capacity in comparison to other forms of attention? And which stimuli-aspects most effectively elicit it? The best method for studying all of these questions would be a repeated-measures design in which multiple experiments are performed on the same group of participants. This simultaneously allows for better evaluation of individual differences, as well as more robust conclusions about the different aspects of stimulus-driven internal attention.

In summary, the current experiment complements earlier research very well, and provides further proof that stimulus-driven internal attention does indeed exist. Furthermore, this form of attention is accompanied by an ocular signature, which consists of a gaze position bias and a microsaccade direction bias. With the exception of the gaze position bias, this ocular signature was also found in the current study. Individual differences seem to play a significant role in a person's capacity for and reaction to involuntary attentional capture, and future research should therefore focus on this as well. Most importantly, this research emphasises that the external world plays an important role in shaping the contents of our mind.

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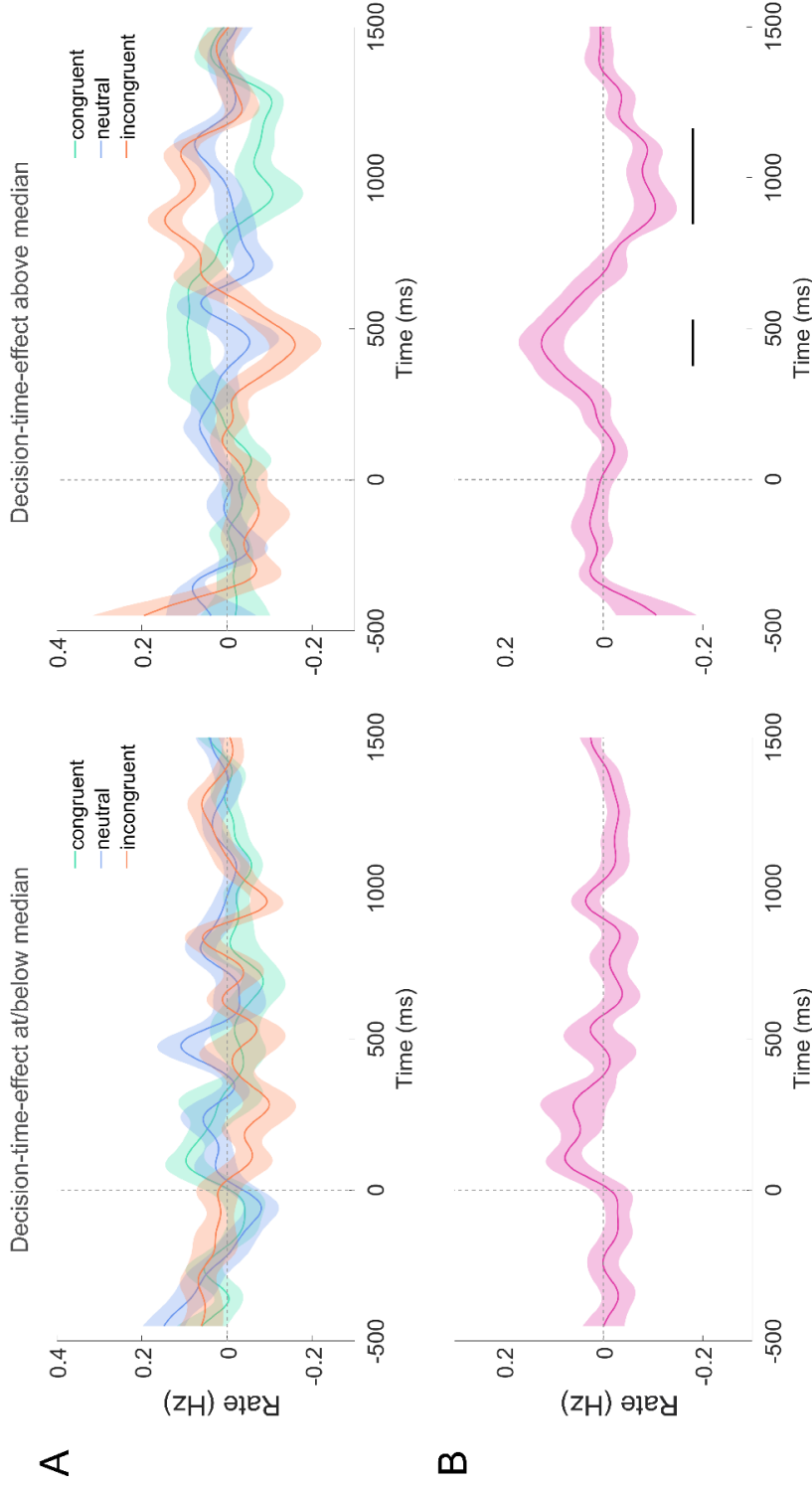
Appendix A: supplementary figures

Figure A1: comparison of toward-vs.-away saccade rate over time for above-median and below/at-median decision time effect groups from experiment 2. *Coloured lines show the average rate of saccades made towards the target memory item in any particular condition, with shaded areas reflecting standard error across participants. Timepoint 0 indicates onset of the capture cue. (A) Overlay of saccade rate toward vs. away over time for congruent, neutral and incongruent conditions, for the below/at-median (left) and above-median (right) decision-time-effect groups. (B) Difference in toward-vs.-away saccade rate between congruent and incongruent conditions, for the below/at-median (left) and above-median (right) decision-time-effect groups. A rate above zero means more saccades were observed towards the target memory item in the congruent condition versus the incongruent condition at that timepoint. Statistical testing was performed on the 0 – 1500 ms time-courses and significantly non-zero time-courses are indicated with a horizontal black line.*
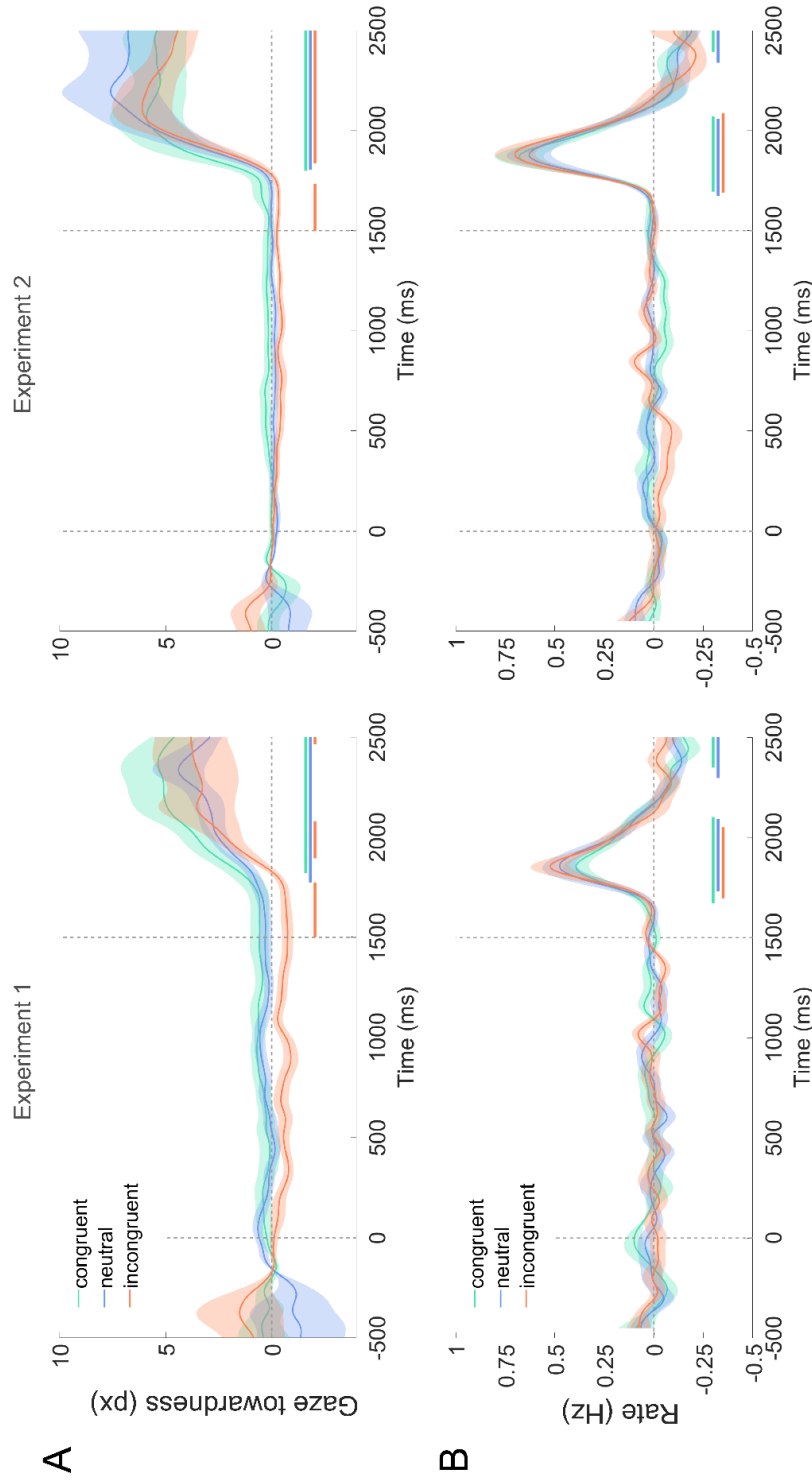
Figure A2: gaze towardness and toward-vs.-away saccade rate over time in congruent, neutral and incongruent trials for experiment 1 and 2, separately. *Timepoint 0 indicates onset of the capture cue. Onset of the probe cue is shown with a dashed line at 1500 ms. Statistical testing was performed on the 1500 – 2500 ms time-course. All significantly non-zero time-courses are visualised with correspondingly-coloured horizontal bars. (A) Coloured lines show average horizontal gaze towardness in the congruent, neutral and incongruent conditions, with shaded areas reflecting standard error across participants. Shown for experiment 1 (left) and 2 (right) separately. (B) Coloured lines show the average rate of saccades made towards the target memory item in the congruent, neutral and incongruent conditions, with shaded areas reflecting standard error across participants. Shown for experiment 1 (left) and 2 (right) separately.*

Appendix B: original code, data and forms

In accordance with open science principles, the following have all been made publicly available. If any of these are no longer findable, or require further explanation, do not hesitate to contact the corresponding author.

Code for visual working memory experiment
The Python code used for both visual working memory experiments is available here:
https://github.com/annavanharmelen/Null-cue-gaze-bias-experiment

Raw data
All raw (anonymised) data that was collected for this research is available here:
https://www.jottacloud.com/s/146245532ecf8414a3abe5fba305e4849f5

Code for analyses
All analysis scripts that were used are available here:
https://www.jottacloud.com/s/14656b52e8cfdb04d1da65eed66c5440dcf

Informed consent and participant instructions
The consent form, the participant information form, and the participant instructions can all be found here:
https://www.jottacloud.com/s/146555ac92e7328480ba0070decc1b8054b