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Original Articles

Social attention directs working memory maintenance

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ABSTRACT

Visual working memory (vWM) performance is enhanced when a memorized object is cued after encoding. This so-called retro-cue effect is typically observed with a predictive (80% valid), retrospective cue. The current study examined whether a nonpredictive (50% valid) retro-cue can similarly enhance internal memory representations in cases where the cue conveys social signals. To this end, gaze cues were presented during the retention interval of a change-detection task, which are capable to engender a mutual attentional focus of two individuals towards one location. In line with our prediction, Experiment 1 demonstrated that a polygon presented at the gazed-at location was remembered better than that at both non-gazed and gazed-away locations. Experiments 2 and 3 showed that low-level motion cues did not elicit attentional orienting in a comparable manner as the gaze cue, and these differences in cuing were found to be reliable and independent of memory load. Furthermore, the gaze retro-cue effect disappeared when the face was inverted (Experiment 4). In sum, these results clearly show that sharing the focus of another individual establishes a point of reference from which visual information is restored with priority, suggesting that a gaze retro-cue leads to social attention, thus, modulating vWM maintenance in a reflexive, automatic manner.

1. Introduction

Visual working memory (vWM) actively maintains a limited proportion of the total sensory input to serve the needs of ongoing tasks, thus providing critical information for adaptive and efficient human behavior in an ever-changing visual environment (see Luck & Vogel, 2013, for a review). The representation of information in vWM is usually assessed with the change-detection task, in which a memory display containing multiple objects is followed by a blank retention interval, after which a test display is presented (Luck & Vogel, 1997). Studies using such a task have shown that observers are capable of maintaining up to four items in vWM, although the exact nature of this capacity limitation is currently a topic of vigorous debate (Luck & Vogel, 2013; Ma, Husain, & Bays, 2014). The contents in vWM are considered to reflect a stable and enduring representation that renders the structural layout in the environment (Nie, Müller, & Conci, 2017), and which is robust to visual interference (Irwin, 1991; Pinto, Sligte, Shapiro, & Lamme, 2013). Recent efforts incorporating spatial cues during the retention interval of a change-detection task (Myers, Stokes, & Nobre, 2017), however, provide a challenge to this rather static conception of vWM representations.

Growing evidence in fact indicates that objects stored in vWM are not fixed and unmodifiable, but are capable of being transformed, or shaped during maintenance. Such a flexible nature of vWM representations is supported by several studies demonstrating that spatial cues, which are presented after encoding can improve vWM performance even though no new information is provided to the observer (Berryhill, Richmond, Shay, & Olson, 2012; Delvenne, Cleeremans, & Laloyaux, 2010; Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; van Moorselaar, Gunseli, Theeuwes, & Olivers, 2015). These cues retroactively manipulate expectations, i.e., by providing a 70% valid cue that informs which of the memorized items will subsequently be relevant. Previous studies using such a task variant have repeatedly demonstrated that such a predictive retro-cue can substantially improve performance (e.g., by 15% relative to a no-cue condition, see Souza & Oberauer, 2016, for a review), thus, suggesting that contents in vWM can be modulated by retroactive shifts of attention.

The extant studies that investigated mechanisms of selective maintenance in vWM mostly used symbolic, non-social retro-cues (e.g., arrows or word cues). However, in everyday life humans often process information based on social cues such as another person's gaze behavior. Indeed, previous work demonstrated that these types of social cues can trigger visuo-spatial orienting of attention: averted gaze of others can automatically induce the observer to shift attention toward the

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location as signaled by the others' gaze direction (e.g., Driver et al., 1999; Friesen & Kingstone, 1998). Such a mutual attentional focus of two individuals towards one single location is known as "social attention". With these variants of spatial cuing paradigms, a series of studies have shown that the gaze direction of a centrally presented face can trigger automatic spatial orienting even if gaze direction does not predict where a target item may appear (i.e., when presenting only 50% valid cues) and/or when the observer is explicitly asked to ignore the cue (Driver et al., 1999; Friesen & Kingstone, 1998). In a typical gaze cuing task, a face would appear at the screen center, with the eyes looking straight ahead initially, after which the eyes avert to the left or right in a subsequent image frame (Bayliss, Paul, Cannon, & Tipper, 2006; Friesen & Kingstone, 1998). Next, a target letter was displayed at either the gazed-at (validly cued) or at the gazed-away (invalidly cued) location. Participants were instructed to categorize the target letters, which revealed a performance advantage for the valid relative to the invalid gaze cue condition (Deaner & Platt, 2003; Driver et al., 1999; Friesen & Kingstone, 1998; Ricciardelli, Bricolo, Aglioti, & Chelazzi, 2002; but see Sun, Stein, Liu, Ding, & Nie, 2017, for a different type of social cue [i.e., biological motion] in orienting unconscious attention). These findings have been taken to suggest that the gaze cue provides a socially and biologically relevant signal that is very efficient in triggering attention shifts.

Although the orienting effects induced by social stimuli as compared to orienting attention by non-social cues is still debated, a number of studies suggested that visuo-spatial orienting due to social and non-social cues leads to diverging behavioral effects that may rely on different underlying processes (Friesen, Ristic, & Kingstone, 2004; Langdon & Smith, 2005) and distinct neural systems (Callejas, Shulman, & Corbetta, 2014; Kingstone, Tipper, Ristic, & Ngan, 2004; Lockhofen, Gruppe, Ruprecht, Gallhofer, & Sammer, 2014). For example, Friesen et al. (2004) used a counterpredictive spatial cuing task to investigate attentional orienting in response to gaze cues as compared to non-social, arrow cues. The task induced a volitional bias in participants to expect that a target will appear at the location opposite to the gazed-at position (i.e., in 75% of trials when the eyes gazed at one side, the target would appear at the other, opposite side). Results indicated that gaze cues not only triggered reflexive orienting of attention to the gazed-at target location but also induced volitional orienting to a likely (i.e., predicted) target location as compared to two baseline locations (two other orthogonal positions) that were neither cued nor predicted. By contrast, only volitional orienting to predicted target locations (vs. baseline locations) was found in the arrow cue condition. These results suggest that social cues are processed differently from non-social cues, and they may in fact be special as they lead to both reflexive and volitional orienting, which are probably subserved by different attentional subsystems (Friesen et al., 2004). Given that orienting of attention in visual perception and in working memory share analogous mechanisms (Harrison & Tong, 2009; Mayer et al., 2007; Serences, Ester, Vogel, & Awh, 2009), it may be equally plausible that distinct behavioral results emerge for a retro-cue that comprises social as opposed to non-social information.

Recent studies that employed a retro-cue paradigm in vWM presenting non-social arrow cues have reported that cue validity modulates the magnitude of the cuing effect (Gunseli, van Moorselaar, Meeter, & Olivers, 2015; Gözenman, Tanoue, Metoyer, & Berryhill, 2014). For example, Gözenman et al. (2014) found a reliable retro-cue effect when the cue validity was 100%, but this effect disappeared when the cue validity decreased to 80%. This suggests that a decrease in cue validity reduces the informative cue value such that observers do not take full advantage of the information that the cue provides, thus leading to a less effective maintenance of items in vWM. By contrast, in a standard gaze cuing experiment, eye gaze was found to trigger reflexive orienting even though the cue did not predict the location where the target would appear (Friesen & Kingstone, 1998). One might therefore assume that such a social cue could reflexively guide individuals' attention to items in working memory even when the predictive value of the gaze cue is rather low. Gregory and Jackson (2017) investigated how gaze cues modulate vWM encoding, in which a vWM task was employed to compare how gaze cues, arrow cues, or non-social motion cues affect vWM encoding for colored squares. The cues were non-predictive of the location where the memory items would appear, but nevertheless, the results indicated that in particular gaze cues (but not arrow or motion cues) affected the encoding of colored squares into vWM. However, this study displayed the gaze cues *before* or *during* the presentation of colored squares and hence only examined the cues' effect on vWM encoding. It has however, been shown that pre-cues versus retro-cues are qualitatively different in typical vWM tasks such as change detection: predictive (e.g., 70% valid) spatial cues *before* the onset of a memory array facilitate the encoding of external representations at the cued location, thus modulating the access of items into vWM, whereas predictive retro-cues *after* the offset of a memory array rather prioritize internal representations at the cued location, i.e., they modulate already-stored object representations (Griffin & Nobre, 2003). To date, it remains unknown how gaze cues impact vWM when the cues appear *after* the offset of a memory array, that is, during maintenance. The current study therefore aimed to examine whether participants could selectively retain items after a nonpredictive gaze cue was presented during the maintenance interval.

The current study presents four experiments, which in each case required participants to memorize two or four polygons. Subsequently, during a retention interval, in Experiment 1, a nonpredictive (50% valid) gaze cue was presented to test whether the direction of gaze influences the vWM representation of the polygons. Next, in Experiments 2 and 3, we compared gaze and comparable motion cues to explore the contribution of low-level kinetic information to the updating of vWM representations under variable memory load. In Experiment 4, inverted faces were then used as retro-cues to further determine whether cuing is related to the social nature of the cues.

2. Experiment 1: gaze retro-cuing

Experiment 1 employed a retro-cue paradigm to examine whether a social (gaze) cue can affect the maintenance of objects in vWM. In this experiment, two polygons were presented in the left and right hemifield of the screen center (see Fig. 1). Participants were asked to remember the shape of these items. The subsequent retention interval then presented a gaze cue, i.e., a face with a neutral expression. After a short delay of 500 ms, the eyes then gazed left, right, or straight ahead for another 500 ms. Thereafter a polygon was presented on the left or right side of a probe array, 500 ms after the offset of the gaze cue. There were three cuing conditions (see Fig. 1). In the *valid* cue condition, the eyes gazed towards the left or right, that is, to the position where the polygon in the subsequent probe display would be presented. In the *invalid* cue condition, the eyes gazed towards the location opposite to the position where the probe display would present a polygon. In the *neutral* cue condition, the eyes looked straight ahead, and the polygon in the probe display was presented on either the left or right side of the screen. The participants were instructed to indicate whether the probe item was identical to the previous memory item at the same position. We predicted that, given the special status of social cues (see above), valid gaze cues should facilitate the maintenance of polygons in vWM as compared to neutral and invalid gaze cues.

2.1. Methods

2.1.1. Participants

Sixteen (9 female; average age: 21.1 years) undergraduate students of Zhejiang University participated in the current experiment. All participants were unaware of the purpose of the experiment. They were all right-handed, and had normal color vision and normal or corrected-to-normal visual acuity. Participants provided written informed consent to

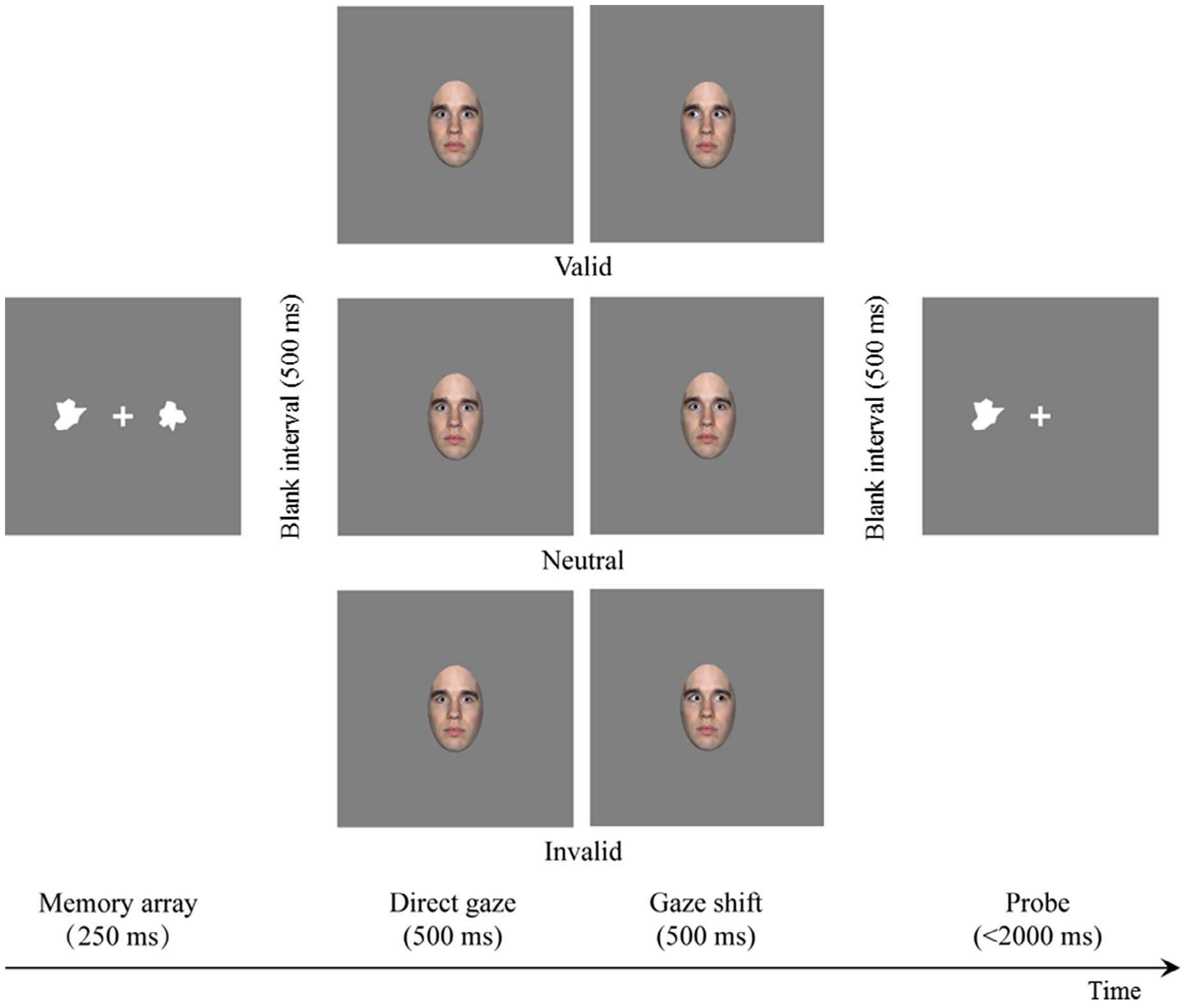

Fig. 1. Example of a display sequence depicting a 'no-change' trial and which presents variants of valid, neutral, and invalid cues (top to bottom panels, respectively) in Experiment 1.

the procedure of the experiment, which was approved by the research ethics committee of Zhejiang University, in accordance with the regulations of the World Medical Association. Participants received 30 RMB/h or course credits.

To ensure adequate power, the sample size was a priori determined by a power analysis based on predicted effect size using G*power 3 (Faul, Erdfelder, Buchner, & Lang, 2009). Based on the results of previous studies (Griffin & Nobre, 2003), we predicted a large effect size (d = 0.68, according to Cohen, 1988) for our experimental design. With 70% power given a 0.05 significance level, the suggested sample size was approximately 16 individuals, which was used for Experiments 1, 2, and 4. All data were included in the analyses reported below, without excluding any data points and observers (this was the case in all subsequent experiments as well. See Appendix for the link to the supplementary data).

2.1.2. Stimuli and apparatus

Six different neutral face images (3 male and 3 female faces, subtending 2.7° × 3.6° each), were used in this experiment. The faces were taken from the NimStim Set of Facial Expressions (Tottenham et al., 2009). To induce the gaze cues in the face images, the position of the iris of the eyes was modified for each face such that the eyes looked left, right or straight ahead. In total, 18 faces (3 gaze directions for each of the 6 faces) were presented in the experiment.

Six different polygons (subtending 1.5° × 1.5° each) as used in Alvarez and Cavanagh (2004) were used as memory items and probes (see Fig. 1), and the changed probe item would not present the nontarget polygons that were shown in the memory array. Each polygon was located 3.5° to the left or right side from the central vertical axis of the display. The experimental material was presented on a 19-inch CRT monitor and on a gray background (8.31 cd/m^2). The refresh rate was 100 Hz and the screen resolution was 1024 × 768 pixels. We used Matlab with Psychtoolbox extensions (Brainard, 1997) to develop and run the experiment.

2.1.3. Procedure

Participants were seated at a distance of about 57 cm from the screen in a dimly lit room. Each trial started with the presentation of a fixation cross for 500 ms, followed by the memory display that presented two polygons which appeared left and right of the central fixation (see Fig. 1) for 250 ms. Participants were instructed to remember the shape of these two patterns. After the presentation of a blank screen for 500 ms, a gaze cue was displayed for 1000 ms at the center of the screen, facing initially straight ahead (500 ms) and then either ahead (neutral cue) or, for valid/invalid cues to the left or to the right (500 ms). After a second blank screen, which was presented again for 500 ms, a probe item was randomly shown with an equal probability on the left or right side of the screen. Observers were asked to judge and respond via key press whether the probed item was the same as that of the preceding memory array at the same location. They were instructed to press the "J" key when the probed item was identical to the memorized item and press the "F" key if there was a difference. Participants completed 24 practice trials to become familiar with the task prior to the formal experiment. They were asked to respond as accurately and as

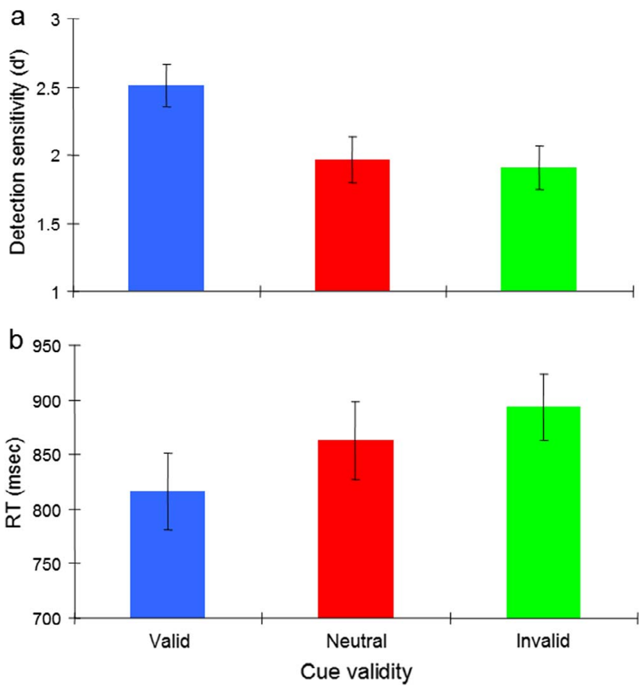

Fig. 2. Results of Experiment 1. Working memory performance: d-prime *d′*, scores (a) and reaction times, RTs (b) are plotted as a function of the validity of the gaze retro-cue (valid, neutral, and invalid). Error bars represent ± 1 standard errors of the mean (SEM).

fast as possible. At the beginning of the experiment, observers were explicitly told that the gaze cue was not predictive of the target location.

The experiment used a two-factor within-subjects design with the factor change (present, absent; indicating the memory-probe transition, which could be either present in half of the trials or absent in the other half) and cue validity (valid, neutral, and invalid cue conditions; see Fig. 1). The experiment consisted of four blocks of 36 trials each, with a total of 144 experimental trials, presented in random order.

2.2. Results and discussion

2.2.1. Detection sensitivity

vWM performance was determined by the signal-detection-theoretic sensitivity measure d-prime (*d′*, see Macmillan & Creelman, 2004). A one-way repeated-measures analysis of variance (ANOVA) on *d′* scores (see Fig. 2a) revealed a significant main effect of cue validity [$F(2, 30) = 12.20$, $p < .001$, $\eta_p^2 = 0.45$]. Post-hoc paired *t*-tests showed that *d′* scores for the valid condition were significantly higher than for the neutral condition [2.51 vs. 1.97, $t(15) = 4.36$, $p < .001$, Cohen's $d = 1.09$], and for the invalid condition [2.51 vs. 1.91, $t(15) = 4.06$, $p = .001$, Cohen's $d = 1.02$], respectively. No significant difference was observed between the neutral and invalid condition [1.97 vs. 1.91, $t(15) = 0.47$, $p = .65$, Cohen's $d = 0.12$].

2.2.2. RTs

To investigate whether there was a speed–accuracy trade-off in our data (i.e., whether accurate responses were issued more slowly on valid than on invalid trials), a one-way ANOVA was conducted on RTs, aggregating correct-response trials only (change present and absent combined) with the factor cue validity (valid, neutral, invalid). The analysis again revealed a significant effect: $F(2, 30) = 14.75$, $p < .001$, $\eta_p^2 = 0.5$. Post-hoc paired *t*-tests indicated that RTs on valid trials were significantly faster than on neutral trials [816 vs. 863 ms, $t(15) = 4.06$, $p = .001$, Cohen's $d = 1.02$; see Fig. 2b], and on invalid trials [816 vs. 894 ms, $t(15) = 4.58$, $p < .001$, Cohen's $d = 1.15$], respectively. No significant difference was again observed for the comparison of the neutral and invalid condition [863 vs. 894 ms, $t(15) = 0.73$, $p = .14$, Cohen's $d = 0.18$]. This pattern of results clearly shows that there was no speed-accuracy trade-off evident in Experiment 1.

These results show that participants performed better under the nonpredictive valid cue condition relative to the invalid and neutral cue conditions. Performance in the neutral condition did not differ from that of the invalid condition. One possibility to account for this lack of a difference might be that in the neutral condition, direct gaze provides a salient signal in itself, which automatically captures attention (Conty, Gimmig, Belletier, George, & Huguet, 2010; Kuhn & Kingstone, 2009; Senju & Johnson, 2009). This may then result in an overall impairment of the memory representations on both sides of the display. By contrast, in the invalid condition, observers need to inhibit the memory representation at the cued location and shift attention to the uncued location in order to perform the task correctly. It thus appears that these two distinct underlying cognitive operations after memory encoding (bilateral inhibition vs. unilateral inhibition and subsequent shift of attention) overall result in equivalent vWM performance. Alternatively, our paradigm might not have been sensitive enough to also detect inhibitory effect in invalid trials given that there were only few items to inhibit.

Irrespective of these processing differences between invalid and neutral cue conditions, Experiment 1 provides the first clear evidence for a reliable gaze retro-cue effect and hence, shows that gaze cues can strengthen the selective maintenance of objects in working memory, even when the cues themselves are not informative.

3. Experiment 2: gaze vs. motion retro-cuing

With symbolic, non-social retro-cues, previous research has indicated that the retro-cue benefit can substantially decrease, or even vanish when invalid cue trials are included in the experiment (Gözenman et al., 2014). In other words, a selective maintenance would not occur when the retro-cue was not informative. In contrast to this result, Experiment 1 revealed a reliable retro-cue benefit with non-informative gaze cues. A possible explanation for this might be that a person's gaze conveys a social signal that is somehow special for processing the memorized items. However, it might also be argued that the effect of attentional orienting to internal representations in vWM induced by gaze cues is not different from other low level, non-social cues (Friesen et al., 2004). In Experiment 2, we therefore compared performance for gaze and motion cues in working memory to determine how low-level kinetic information, i.e., the movement of the eyes, influences the gaze retro-cue effect irrespective of a potential socially relevant signal. To this end, a non-social motion cue was designed, which presented two dots on a line segment that could move slightly to the left or right, thus reproducing comparable motion signal as provided by the pupils in the gaze cue (see Fig. 3). If the results from Experiment 1 were due to low-level kinetic stimulus information, then we would anticipate a similar impact of the motion cues on internal vWM representations.

3.1. Methods

3.1.1. Participants

Sixteen (9 female; mean age 22.7 years) naïve undergraduate students of Zhejiang University participated in this experiment in exchange for course credits or monetary reimbursement (30 RMB/h). All participants were right-handed, and had normal color vision and normal or corrected-to-normal visual acuity.

3.1.2. Stimuli and apparatus

The gaze cues used in this experiment were identical to those of Experiment 1. We introduced a new retro-cue, which was intended to match the physical properties of the gaze cue, by placing two dots on a line segment. Note that the size of the dots was the same as the pupil

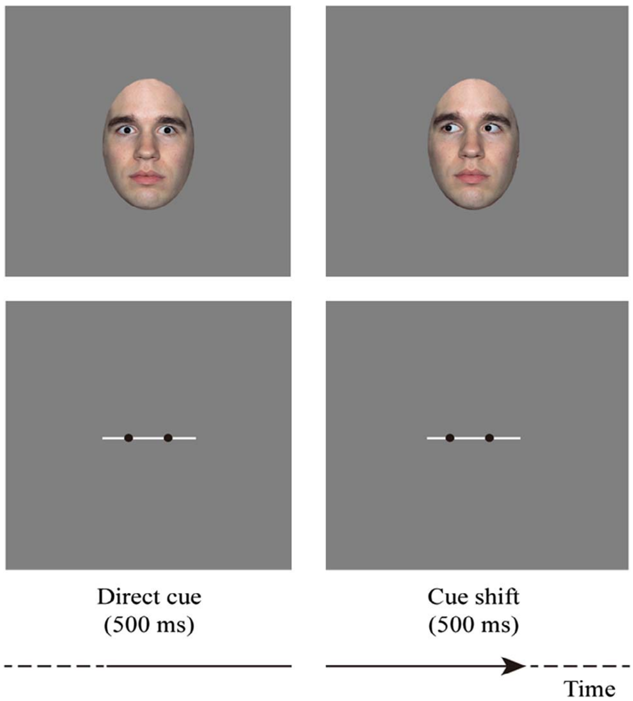

Fig. 3. Examples of the gaze and motion retro-cues used in Experiment 2 (top and bottom panels, respectively), presenting a leftward cue shift in both variants.

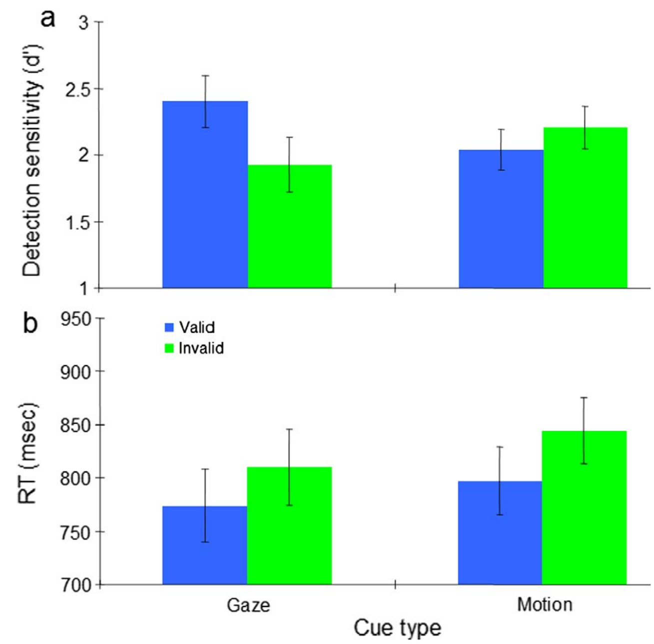

Fig. 4. Results of Experiment 2. Working memory performance in *d′* scores (a) and RTs (b) is plotted as a function of cue type (gaze, motion) separately for valid and invalid cue conditions. Error bars represent ± 1 SEM.

size of the gaze cue, and the length of the line segment was the same as the width of the presented face images. When the dots were moving, their displacement was just the same as that of the pupils in the gaze cue. That is, the two dots moved horizontally towards the left or right relative to their original locations on the line segment. The moving distance of the dots was identical to that of the pupils in Experiment 1 (see Fig. 3). All other details of the experiment were comparable to those of Experiment 1.

3.1.3. Procedure

A 2 (change: present vs. absent) × 2 (cue type: gaze vs. motion) × 2 (cue validity: valid vs. invalid) within-subjects design was used in Experiment 2. There were 4 blocks in the formal experiment (presenting 2 blocks with gaze cues and 2 blocks with motion cues). Each block consisted of 48 trials with 24 valid cue trials and 24 invalid cue trials, presented in random order in each block. The order of the gaze-cue and motion-cue blocks was counter-balanced across observers. For both gaze-cue and motion-cue blocks, participants completed 16 practice trials to be familiar with the corresponding task. There were overall 192 trials in the formal experiment.

3.2. Results and discussion

3.2.1. Detection sensitivity

The *d′* scores were entered into a 2 × 2 repeated-measures ANOVA with the within-subject factors cue type (gaze, motion) and cue validity (valid, invalid). The main effect of cue type was not significant [$F(1, 15) = 0.08$, $p = .78$, $\eta_p^2 = 0.006$], but the main effect of cue validity approached significance [valid vs. invalid: 2.22 vs. 2.07, $F(1, 15) = 4.42$, $p = .053$, $\eta_p^2 = 0.23$], with the corresponding effect size (< 0.3) being suggestive of a marginally reliable evidence for a higher detection sensitivity for valid (vs. invalid) cue condition. More importantly, there was a significant interaction between cue type and cue validity [$F(1, 15) = 7.33$, $p = .016$, $\eta_p^2 = 0.33$, see Fig. 4a]. The interaction showed that there was a cuing effect only in the gaze cue condition: when the polygon was presented at the gazed-at location, *d′* values were significantly higher than when the polygon was presented on the not gazed-at location [valid vs. invalid: 2.40 vs. 1.93, $t(15) = 4.72$, $p < .001$, Cohen's $d = 1.18$]. By contrast, in the motion cue condition, there was no significant difference between valid and invalid cues, actually revealing a numerical cost of the valid motion cues [valid vs. invalid: 2.04 vs. 2.20, $t(15) = 0.97$, $p = .35$, Cohen's $d = 0.24$].

3.2.2. RTs

To again test a potential speed–accuracy trade-off, a 2 × 2 repeated-measures ANOVA was conducted on RTs from correct trials (combining change and no-change trials) with the factors cue type (gaze, motion) and cue validity (valid, invalid). The main effect of cue validity was significant (see Fig. 4b), valid vs. invalid: 786 vs. 827 ms, $F(1, 15) = 10.31$, $p = .006$, $\eta_p^2 = 0.41$. Neither the main effect of cue type nor the interaction between cue validity and cue type were significant (*ps* > .21), indicating that the valid items were identified significantly faster than the invalid items for both gaze and motion cues. These data thus show that there was no speed–accuracy trade-off.

Overall, the results from Experiment 2 suggest that valid gaze and motion cues can both speed up probe responses. However, as evident from the d′ analyses, a nonpredictive gaze cue is additionally more powerful in guiding attention to internal representations during working memory maintenance, while also facilitating the memory-probe comparison to a larger extent than a comparable non-social, motion cue.

4. Experiment 3: retro-cuing under variable memory load

The experiments reported so far always used a relatively low set size, which required observers to memorize two polygons on a given trial. Previous work has repeatedly demonstrated that such rather complex objects usually reveal a rather low working memory capacity of only 1 or 2 items (Alvarez & Cavanagh, 2004; Luria, Sessa, Gotler, Jolicœur, & Dell'Acqua, 2010). However, the change detection task, which relies on recognition, might nevertheless have resulted in a comparably high level of performance, especially since only six different polygons were presented overall throughout the experiments. This limited stimulus set might have increased the familiarity of the

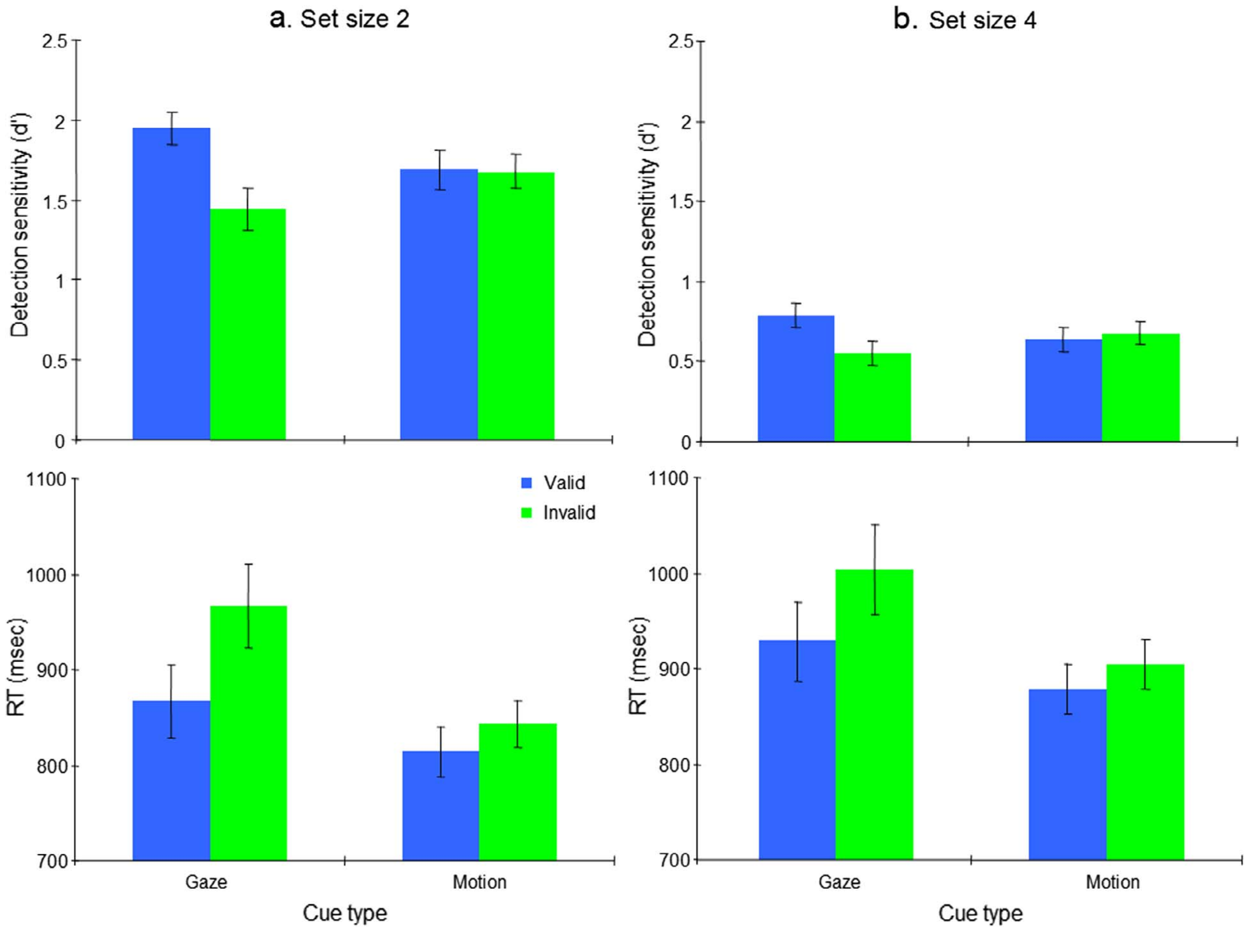

Fig. 5. Results of Experiment 3. Working memory performance in *d′* scores (a and b, upper panel) and RTs (a and b, lower panel) is plotted as a function of cue type (gaze, motion), separately for valid and invalid cue conditions for set size 2 (a) and 4 (b). Error bars represent ± 1 SEM.

polygons to be memorized. In order to address these issues, in Experiment 3 we increased the number of candidate polygons from the initial set of 6 possible items to a set of 24 randomly generated polygon objects, thus, now providing an increase in stimulus variability. In addition, we also introduced a larger memory load (presenting displays with a set size of 4 items). We predicted that if gaze retro-cues can effectively enhance performance irrespective of the memory load, then a cuing benefit should again replicate across the various set sizes (2 and 4). We also expected that the gaze retro-cue should be more effective in guiding attention to an internal representation than a non-social motion cue (comparable to the pattern as observed in Experiment 2).

An additional goal of Experiment 3 was to test the stability and replicability of the gaze retro-cuing effect in a larger sample of observers. To this end, the sample of observers was increased in order to achieve a higher (90%) power for the respective analyses.

4.1. Methods

4.1.1. Participants

Twenty-six (16 female; mean age 20.7 years) new observers of Zhejiang University participated in this experiment in exchange for course credits or monetary reimbursement (30 RMB/h). The sample size was determined by a power analysis based on a predicted effect size of 0.68 with 90% power using G*power 3 (Faul et al., 2009). All participants were right-handed, and had normal color vision and normal or corrected-to-normal visual acuity.

4.1.2. Stimuli and apparatus

We introduced a new factor – set size (2 and 4), in order to replicate Experiment 2 and additionally, to extend the effect of retro-cues on performance to a higher, more demanding memory load (i.e., set size 4). The polygons were presented within two 4° × 6° rectangular regions that were centered 3° to the left and right of a central fixation cross. Stimulus positions were randomized on each trial, with the constraint that the distance between objects within a hemifield was at least 2.3° (center to center). In order to rule out any potential influences of familiarity, we also increased the number of candidate polygons from 6 to 24, which were randomly generated in the same way as in the previous experiments. All other details of the experiment were comparable to those of Experiment 2.

4.1.3. Procedure

A 2 (change: present vs. absent) × 2 (set size: 2 or 4) × 2 (cue type: gaze vs. motion) × 2 (cue validity: valid vs. invalid) within-subjects design was used in Experiment 3. There were 8 blocks in the formal experiment (presenting 4 blocks with gaze cues and 4 blocks with motion cues). Each block consisted of 48 trials with 24 valid cue trials and 24 invalid cue trials half of which presented set size 2 and the other half set size 4 displays. Trials were presented in random order in each block. The order of the gaze-cue and motion-cue blocks was counterbalanced across observers. For both gaze-cue and motion-cue blocks, participants completed 32 practice trials to become familiar with the corresponding task. There were overall 384 trials in the formal experiment.

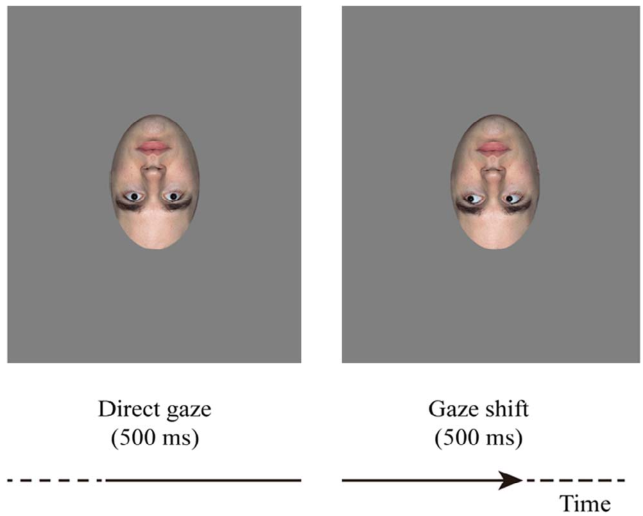

Fig. 6. An example of the retro-cues used in Experiment 4, presenting inverted faces.

4.2. Results and discussion

4.2.1. Detection sensitivity

The d' scores were entered into a $2 \times 2 \times 2$ repeated-measures ANOVA with the within-subject factors set size (2, 4), cue type (gaze, motion), and cue validity (valid, invalid). The main effects of both set size [2 vs. 4: 1.69 vs. 0.66, $F(1, 25) = 149.39$, $p < .001$, $\eta_p^2 = 0.86$] and cue validity [valid vs. invalid: 1.27 vs. 1.09, $F(1, 25) = 15.14$, $p = .001$, $\eta_p^2 = 0.38$] were significant, while the main effect of cue type [$F(1, 25) = 0.02$, $p = .88$, $\eta_p^2 = 0.001$] was not, suggesting that both memory load and cue validity modulate change-detection sensitivity. More importantly, there was a significant interaction between cue type and cue validity [$F(1, 25) = 11.49$, $p = .002$, $\eta_p^2 = 0.32$, see Fig. 5a and 5b, upper panel]. This interaction replicated our previous findings on the gaze retro-cuing effect for both set sizes 2 and 4: when the polygons were presented at the gazed-at location, d' values were significantly higher than when the polygons were presented on the gazed-away location [valid vs. invalid: 1.37 vs. 1.0, $t(25) = 4.87$, $p < .001$, Cohen's $d = 0.96$]. By contrast, for motion cues, the cuing effect was not observed at both set sizes ($p > .84$). The results show that a reliable gaze retro-cue effect occurs independently of memory load, while not being evident in the non-social motion cue. All the other two-way and three-way interactions of interest were not significant ($ps > .14$).

4.2.2. RTs

To again test for a potential speed–accuracy trade-off, a $2 \times 2 \times 2$ repeated measures ANOVA was conducted on RTs from correct trials (combining change and no-change trials) with the factors set size (2, 4), cue type (gaze, motion), and cue validity (valid, invalid). The main effects of set size [2 vs. 4: 827 vs. 927 ms, $F(1, 25) = 14.55$, $p = .001$, $\eta_p^2 = 0.37$], cue type [gaze vs. motion: 935 vs. 854 ms, $F(1, 25) = 7.4$, $p = .012$, $\eta_p^2 = 0.23$], and cue validity [valid vs. invalid: 867 vs. 923 ms, $F(1, 25) = 43.67$, $p < .001$, $\eta_p^2 = 0.64$] were all significant. Interestingly, there was also a significant interaction between cue type and cue validity [$F(1, 25) = 17.47$, $p < .001$, $\eta_p^2 = 0.41$, see Fig. 5a and 5b, lower panel]. This interaction shows that gaze cues were more effective than motion cues in guiding internal attention, thus speeding up the response (cuing effect were 89 ms and 28 ms for gaze and motion cues, respectively). Post-hoc paired t-tests [$t(25)$s > 5.05, $ps < .001$] revealed again that responses for valid cues were significantly faster than responses for invalid cues for both gaze and motion cues. All other two-way and three-way interactions were not significant ($ps > .2$). These data again show that there was no speed–accuracy trade-off.

In summary, our results from Experiment 3 replicated that valid gaze and motion cues can both speed up probe responses irrespective of memory load, but in addition, a non-predictive gaze cue is more powerful in guiding attention to internal representations during working memory maintenance, thus facilitating memory-probe comparison to a larger extent than a comparable non-social, motion cue. This pattern of performance was found to be independent of memory load, i.e., it revealed a comparable outcome irrespective of the number of objects in a memory array, thus, effectively replicating our findings with a larger sample of observers.

5. Experiment 4: retro-cuing with inverted faces

Although previous experiments provide consistent evidence to support the view that the selective maintenance on the basis of a non-informative gaze cue is effective in modulating the prioritization of internal object representations, it could nevertheless be argued that some low-level characteristics of the face stimulus may be responsible for the observed effect. To address this issue directly, we performed a further control experiment that presented vertically inverted faces as retro-cues. If low-level structures of the face alone determine the gaze retro-cue effect, then this effect should not be influenced by face inversion.

5.1. Methods

Sixteen (5 female; mean age 20.3 years) naïve observers from Zhejiang University participated in this experiment for course credits or monetary reward (30 RMB/h). All observers were right-handed, and had normal color vision and normal or corrected-to-normal visual acuity.

The faces used in previous experiments were vertically inverted in Experiment 4 (see Fig. 6). The experiment included two gaze cue blocks. Each block consisted of 48 trials with 24 valid gaze cue trials and 24 invalid gaze cue trials presented in random order. Participants completed 16 practice trials to become familiar with the task. There were 96 trials in the formal experiment. All other details were identical to Experiment 1.

5.2. Results and discussion

5.2.1. Detection sensitivity

The d' scores of the valid and invalid cue conditions were analyzed with a paired-samples t-test (see Fig. 7a). No significant difference was observed between the two conditions [valid vs. invalid: 2.08 vs. 1.91, $t(15) = 1.16$, $p = .26$, Cohen's $d = 0.29$]. In a subsequent step, the overall validity effect was computed by subtracting the d′ scores of the invalid condition from the valid d′ scores. A comparison of the validity effects between Experiments 2 and 4 by means of an independent-samples t-test resulted in a significant difference, $t(30) = 1.76$, $p = .044$, Cohen's $d = 0.62$, with the validity effect being larger in Experiment 2 than in Experiment 4 (0.48 vs. 0.17; see Fig. 7c).

5.2.2. RTs

The main effect of cue validity was again not significant (see Fig. 7b), valid vs. invalid: 788 vs. 798 ms, $t(15) = 0.75$, $p = .47$, Cohen's $d = 0.19$, indicating that there was no speed–accuracy trade-off in Experiment 4. The overall validity effect (i.e., invalid minus valid in RTs) was also compared between Experiments 2 and 4: however, an independent-samples t-test revealed only a marginal significance, $t(30) = 1.5$, $p = .072$, Cohen's $d = 0.53$, which indicates that the validity effect tends to be larger with upright than with inverted face cues (36 vs. 9 ms; see Fig. 7d).

In summary, the gaze retro-cue effect on the selective vWM maintenance vanished on both detection sensitivities and RTs by face inversion. This indicates that the gaze retro-cue effect as reported in the

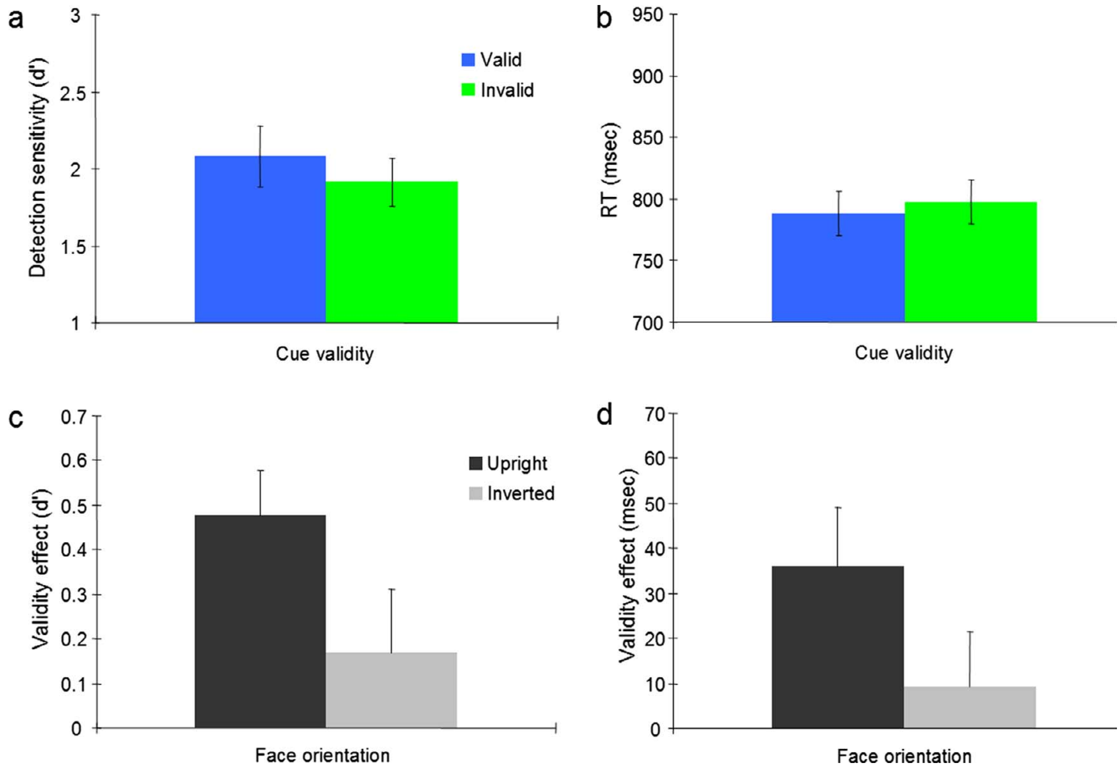

Fig. 7. Results of Experiment 4. Mean *d′* scores (a) and RTs (b) are plotted as a function of the validity of the inverted gaze retro-cue (valid, invalid). In addition, validity effects in *d′* (c) and for the RTs (d) are plotted as a function of the orientation of the face retro-cue, i.e., for upright (Experiment 2) and inverted (Experiment 4) faces. Error bars represent ± 1 SEM.

previous experiments is due to configural face processing rather than a result of the local features of the presented face stimuli.

6. General discussion

The aim of the current study was to determine whether social attention can influence the maintenance of complex objects in vWM. To this end, we combined gaze-cuing with a change-detection task using complex polygon shapes as to-be-memorized items (Experiment 1). To further investigate the social determinants of the gaze retro-cue effect, and to determine whether the obtained results reflected social attention as compared to a more general attentional effect by nonsocial, physical cues, Experiments 2 and 3 employed a low-level motion cue to determine the contribution of kinetic, directional information to gaze cuing under variable memory load. Finally, in Experiment 4 we inverted the facial images used to induce gaze cues in order to test the role of basic perceptual features given by face stimuli in cuing attention. All experiments presented valid and invalid cues (except for an additional neutral cue condition where the eye gaze remained directed towards the center in Experiment 1), and cues were completely nonpredictive of the subsequent probe location. Experiments 1 and 2 consistently showed that the gaze and motion cues both reliably oriented attention to speed localization of the target on valid versus invalid trials. However, only gaze cues influenced vWM storage, revealing a higher detection sensitivity for polygons presented at the gazed-at location by the valid face cue as compared to the face cue which looked away from the changed item (invalid) and face cues without the gaze being directed to one side (neutral). Moreover, the gaze retro-cuing effect was found to be independent of memory load and it was not influenced by the familiarity of the to-be-memorized stimulus set (Experiment 3). In contrast to these clear effects for gaze cues, the motion cue and the inverted gaze cue did not influence vWM sensitivity, indicating that the effects of gaze retro-cues on vWM are specifically related to social relevance, and cannot be attributed to low-level motion signals as induced by the pupils or basic perceptual features of the faces. Thus, our data best fit with a model that assumes certain facilitation by social attention, as we find no performance cost for the invalid, relative to the neutral condition in Experiment 1. It seems that the two distinct underlying cognitive operations after memory encoding (unilateral inhibition and subsequent shift of attention [invalid condition] vs. bilateral inhibition [neutral condition]) overall result in comparable vWM performance. Overall, we find consistent evidence for gaze-induced facilitation, indicating that jointly attended information appears to have received special priority during working memory maintenance.

Increased attention has been shown to enhance perceptual processing (e.g., Carrasco, Ling, & Read, 2004; Pestilli & Carrasco, 2005), and the close connection between attention and vWM (Cowan et al., 2005) may suggest that enhanced vWM for polygons that were reinforced by a gaze retro-cue simply reflects some general increase of attention during maintenance. For instance, Gözenman et al. (2014) compared performance in retro-cues with 100% and 80% validity. Retro-cue benefits were substantially reduced under the condition with relatively lower (80%) validity. That is, retro-cue effects appear to depend on the ratio of cue validity, indicating that people use the cue information strategically to modulate vWM maintenance. It may, therefore, seem straightforward to also observe a vWM benefit for items reflexively cued by gaze. However, the clear absence of any reliable retro-cue effects on vWM using non-social motion cues and inverted face cues suggests that the effect might be a result of mutual attentional allocation to internal representations at the reflexively cued location resulting in enhanced maintenance of the polygons.

In fact, gaze cues indicate more than just a directionality of interest, they indicate the intent to act upon an interest and thus engage in goal-directed behavior (e.g., Johansson, Westling, Bäckström, & Flanagan, 2001; Land, Mennie, & Rusted, 1999; Land & Tatler, 2009). Thus, engaging in social attention not only results in a shift of attention towards the cue location, but also in a shared focus of attention and corresponding shared goals, which is important for predicting imminent behavior and to enable future collaboration (Huang, Andrist, Sauppé, & Mutlu, 2015). We tend to remember things that are important to our goals (Altmann & Trafton, 2002; Montagrin, Brosch, & Sander, 2013), and raising the value of information via social attention may serve to enhance goal-directed vWM processes. The motion and inverted gaze cues simply provide directional information but hardly signal any goal-directed intent. This could be a likely explanation for why the nonsocial cues do not influence sensitivity towards vWM representations in our study, but do influence the speed to locate a target in a similar manner as gaze cues. The role of intent in gaze cues can also help to explain the influence of gaze but not arrow cues on long-term memory (Dodd, Weiss, McDonnell, Sarwal, & Kingstone, 2012).

Our finding that vWM representations are influenced by non-predictive gaze retro-cues but not nonsocial retro-cues also lends further support to the broader notion that not all attentional orienting is the same, and that social attention may be a special case. For instance, there is an ongoing debate as to whether gaze and arrow cues operate on different attentional systems. Many traditional cuing tasks that involve detection, localization, or discrimination of a simple target find a similar time course of cuing effects for gaze and arrow cues, and show that both cues can elicit a mixture of reflexive (exogenous) and volitional (endogenous) orienting responses (Galfano et al., 2012; Tipples, 2002). However, Hietanen, Nummenmaa, Nyman, Parkkola, and Hämäläinen (2006) found that, despite showing similar behavioral cuing effects, a distinct non-overlapping cortical network mediated orienting to gaze cues compared with arrow cues, suggesting that social attention engages in specific neuronal networks. In addition, Kingstone et al. (2004) devised an ambiguous stimulus that could either be perceived as a cartoon face with a large hat (in which case the critical features would serve as gazing eyes) or a cartoon car (in which case the same features would serve as wheels). They found robust cuing effects only when the stimulus was referred to as a face, but not when it was perceived as a nonface object; and further showed that activity in superior temporal sulcus, which is known to be involved in processing social signals, was higher in the face than in the car condition. Together, these findings suggest that allocating attention on the basis of a socially relevant signal might enhance its behavioral relevance and it appears to be conveyed by specialized neuronal structures.

In conclusion, the present study provides novel evidence that attentional orienting toward a gazed-at vWM representation is reflexive, in the sense that it occurs when observers do not have any incentive to enhance the internal object representation at the gazed-at location. Our findings imply that although many directional cues might trigger reflexive shifts of attention when they are spatially nonpredictive, they are not all equal in modulating vWM maintenance. In particular, gaze cues are more strongly reflexive to internal object representations than comparable motion cues, possibly because they access a neural architecture that is specialized for processing gaze direction.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.10.025.

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