Mem Cogn (2016) 44:740–749
DOI 10.3758/s13421-016-0599-6

Dimension-based attention in visual short-term memory

Michael Pilling[1] · **Doug J. K. Barrett**[2]

Abstract We investigated how *dimension-based attention* influences *visual short-term memory* (VSTM). This was done through examining the effects of cueing a feature dimension in two perceptual comparison tasks (change detection and sameness detection). In both tasks, a memory array and a test array consisting of a number of colored shapes were presented successively, interleaved by a blank interstimulus interval (ISI). In Experiment 1 (change detection), the critical event was a *feature change* in one item across the memory and test arrays. In Experiment 2 (sameness detection), the critical event was the *absence of a feature change* in one item across the two arrays. Auditory cues indicated the feature dimension (color or shape) of the critical event with 80 % validity; the cues were presented either prior to the memory array, during the ISI, or simultaneously with the test array. In Experiment 1, the cue validity influenced sensitivity only when the cue was given at the earliest position; in Experiment 2, the cue validity influenced sensitivity at all three cue positions. We attributed the greater effectiveness of top-down guidance by cues in the sameness detection task to the more active nature of the comparison process required to detect sameness events (Hyun, Woodman, Vogel, Hollingworth, & Luck, *Journal of Experimental Psychology: Human Perception and Performance*, *35*; 1140–1160, 2009).

Keywords Visual short-term memory · Dimension-based attention · Change detection · Sameness detection

Visual short-term memory (VSTM) is the capacity to retain visual information in an active form for several seconds after viewing (Luck & Vogel, 1997; Pashler, 1988). A distinct characteristic of VSTM—differentiating it from both iconic memory and visual long-term memory—is its restricted capacity. Estimates suggest that a maximum of around three to four objects can be retained at any moment (Cowan, 2001; Vogel, Woodman, & Luck, 2001), though there is an ongoing debate over whether this limit is manifested in terms of fixed object slots or of a more flexible cognitive resource that allows some trade-off between precision and capacity (see Luck, 2008).

VSTM underlies our ability to visually compare objects over space and time, a function that is necessary for a number of important cognitive operations, such as category learning (Markman & Gentner, 2000). The role of VSTM in mediating visual comparisons can be seen in the *change detection* paradigm (Luck & Vogel, 1997; Pashler, 1988; Vogel et al., 2001). For instance, Vogel et al. in one experiment presented observers with a memory display containing from four to 12 colored squares. The offset of this display was followed, after a 900-ms blank interval, by a test display. On half of the trials, the test display was identical to the memory display. On the other half, one item changed color (e.g., a previously red square became blue). Participants were required to report whether or not a color change had occurred on each trial. When the display contained just four items, change detection sensitivity was relatively high (around 70 % correct). However, sensitivity declined markedly as the number of items increased to 12 items, a result that was attributed to limits in the capacity of VSTM (Luck & Vogel, 1997). Other evidence has shown that observers are often strikingly poor in

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✉ Michael Pilling
mpilling@brookes.ac.uk

[1] Psychology, Faculty of Life and Health Sciences, Oxford Brookes University, Oxford OX3 0BP, UK

[2] Department of Neuroscience, Psychology and Behaviour, University of Leicester, Leicester LE1 7HB, UK

their ability to detect changes in naturalistic scenes and multi-item displays, even after viewing the pre- and postchange displays across several iterations, a phenomenon dubbed *change blindness* (Rensink, 2000; Rensink, O'Regan, & Clark, 1997; see Simons & Rensink, 2005, for a review).

The restrictive capacity of VSTM means that it is not just to changes we show blindness, but also to things *that do not change*. This fact can be demonstrated in the *sameness detection* task (Davis & Leow, 2005; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Wilson & Goddard, 2011). This is similar in many respects to the change detection task: A memory array is presented, which is followed after a blank interval by a test array. The key difference, however, is that the critical event is the *absence of a change* (i.e., one item remains the same across the memory and test arrays while all other items change). Evidence indicates that sameness detection is often less accurate than change detection (Davis & Leow, 2005; Farell, 1985; Taylor, 1976; cf. Theeuwes, 2004), an asymmetry that persists even when judgments concern the same memory and test pair given under different task instructions (Hyun et al., 2009).

This advantage for change over sameness detection appears to reflect a general tendency for the visual system to be sensitive to the presence of new information (Christ & Abrams, 2006; Jonides & Yantis 1988). The advantage may be a consequence of the way in which the visual system makes comparisons between information held in memory and the current input. For change detection, provided that the relevant information is held in VSTM, the mismatch between memory and the current input generates a transient that draws attention to the change item in a reflexive manner; for sameness detection, no such transient is produced by the correspondence between memory and the current input, meaning that no bottom-up guidance is given (Hyun et al., 2009). The consequence of this is that sameness events tend to be inherently less salient than changes.

One thing that is apparent for VSTM comparison tasks such as change and sameness detection is the role played by *attention*. Sensitivity to change or to sameness events tends to dramatically increase when attention, through cueing or other methods, is directed to the location of the relevant item (Rensink et al., 1997; Scholl, 2000; Smith & Schenk, 2008; Tse, 2004; Wilson & Goddard, 2011). What aspect(s) of VSTM processing are susceptible to such a spatial attentional influence? One possibility is that attention affects encoding processes. Attention is generally considered the “gatekeeper” for VSTM; indeed, spatial attention seems to be a prerequisite for items to become encoded into VSTM (Averbach & Coriell, 1961; Awh, Vogel, & Ohr, 2006; Sperling, 1960; Wolfe, Reinecke, & Brawn, 2006). However, other evidence has shown that directions of spatial attention can influence VSTM even after encoding has taken place; cues presented during the retention interval also have a reliable effect on performance. This indicates that attentional prioritization can occur within VSTM in the absence of perceptual input (Griffin & Nobre, 2003; Makovski, 2012; Matsukura, Cosman, Roper, Vatterott, & Vecera, 2014). Furthermore, some evidence suggests that valid spatial cues can facilitate performance when they are presented concurrently with the test stimulus (Beck & van Lamsweerde, 2011; Hollingworth, 2003). Such late cueing effects are presumably a consequence of *uncertainty reduction* (Luck, Hillyard, Mouloua, & Hawkins, 1996), in which the cue allows the relevant comparison and decision processes to be limited to the critical location.[1]

Attention is not just spatial in nature. It can also be directed to toward specific *feature values* (e.g., red) or *feature dimensions* (e.g., color), modes of attentional selection that have been termed, respectively, *feature-based* and *dimension-based attention* (see Müller, Reimann, & Krummenacher, 2003).[2] These modes of selection have been shown to be independent of spatial attention (Maunsell & Treue, 2006); their effects seem to be global across the visual field (Hayden & Gallant, 2005; Lustig & Beck, 2012).

The interest in the present article is to understand the impact on VSTM processes when attention is directed toward one particular feature dimension. Evidence suggests that dimension-based attention is something that, at least in part, is under endogenous control (Krummenacher & Müller, 2012). Such control can be manifested by task instruction, by the presentation of cues, or by varying the trial-to-trial probability of the critical feature dimension (Liu, Slotnick, Serences, & Yantis, 2003; Meiran, Dimov, & Ganel, 2013; Töllner, Zehetleitner, Gramann, & Müller, 2010; Wolfe, Butcher, Lee, & Hyle, 2003; see Memelink & Hommel, 2013).

In the context of VSTM, research has shown that performance is affected when attention is directed toward or away from the critical dimension on a given trial or set of trials (Aginsky & Tarr, 2000; Austen & Enns, 2003; Droll, Hayhoe, Triesch, & Sullivan, 2005; Triesch, Ballard, Hayhoe, & Sullivan, 2003; van Lamsweerde & Beck, 2011; Yang, Chang, & Wu, 2013). For example, van Lamsweerde and Beck used a change detection paradigm in which observers had to report which of several items changed between a memory and a test display. The change on each trial could be

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[1] It must be noted that these uncertainly reduction effects have not been reliably found in all change detection studies in which such late cues have been presented. These spatial postcue effects tend to be found mostly in experiments in which the stimuli consist of naturalistic scenes, and postcues have been found to be ineffective in experiments in which the stimuli are arbitrary geometric shapes (Becker, Pashler, & Anstis, 2000; Luck & Vogel, 1997; Sligte, Scholte, & Lamme, 2008; see Beck & van Lamsweerde, 2011, for further discussion of this issue).

[2] This nomenclature is not consistent across the literature. Some authors, for instance, use *feature-based attention* as a generic term to describe the attentional selection of feature dimensions as well as feature values (e.g., Flevaris & Murray, 2015; Liu et al., 2003; Maunsell & Treue, 2006).

to an item's color, shape, or location. The probability with which the three different types of changes occurred was varied across participant groups in an initial block of trials. All participants then completed an additional block in which the three types of changes occurred with equal probabilities. The accuracy with which different types of changes were detected in the latter block depended on the frequency with which that change had been experienced by the group in the initial trial block; sensitivity tended to be greatest to the most frequently occurring change type. This effect presumably reflects the way that observers weighted attention toward the different features in response to the probability manipulation in the initial block.

The dimensional effects identified by van Lamsweerde and Beck (2011) are not restricted to change detection. Pilling and Gellatly (2013) observed similar effects using a different type of VSTM task: an abrupt-probe task (Pilling & Gellatly, 2011; Wolfe et al., 2006). In the task, participants viewed a display containing from nine to 36 colored shapes. After a delay, a probe occluded one item, and the participant's task was to report a feature of the occluded item (its color or its shape). The report feature varied unpredictably from trial to trial and was indicated by an auditory cue presented simultaneously with the probe's onset. The relative frequencies of the color and shape report trials were varied across two participant groups. An effect similar to that reported by van Lamsweerde and Beck was found: Observers were most accurate when reporting the feature dimension with the higher report frequency. This advantage was independent of set size effects, indicating that the attentional effect of the frequency manipulation was global in its extent, influencing all items in the viewed display (Hayden & Gallant, 2005).

Thus, there is clear evidence that dimension-based attention, like spatial attention, can influence the accuracy of VSTM, whether this is measured in terms of change detection performance or the accuracy with which previously viewed features can be reported. Performance seems to be improved when the task conditions bias attention toward the critical dimension for a trial, as compared to trials in which attention is misdirected. However, unlike for spatial attention, the manner in which dimension-based attention influences VSTM has yet to be investigated. For instance, in the context of VSTM, does dimension-based attention only influence encoding operations, or does it also influence later-stage processes—for instance, those associated with comparisons and perceptual decisions?

Here we investigated two perceptual comparison tasks, change detection (Exp. 1) and sameness detection (Exp. 2), in pursuit of this question. We briefly presented to observers both a memory and a test array consisting of colored shapes, separated by a blank interstimulus interval (ISI). In the change detection task, observers had to detect a *feature change*: On critical trials, the feature value of one object (on either the color or the shape dimension) changed across the memory and test displays, while all other objects stayed the same. In Experiment 2 (sameness detection), the critical event was the *absence of a feature change*. Here the task was to detect whether any object had retained one of its feature values (either its color or shape) across the memory and test displays, while all of the other features changed. In both experiments, a verbal cue indicated the feature dimension of the critical event on that trial (i.e., the dimension of the feature that changed or remained constant). A valid–invalid manipulation was used to determine the cue effectiveness: On most trials, the critical feature dimension was validly cued, but on a subset of trials the cues misdirected attention to the incorrect dimension (Posner, 1980; Wegener et al., 2008).

The experiments had three specific aims. The first was to establish whether dimension-based attention influences VSTM. As we have seen, much of the evidence for this has been based on change or task probability manipulations, which arguably conflate top-down attentional effects with those of extended practice. The use of a cueing method in the present experiments provides a more direct measure of the effect of attention itself. The second aim was—by varying the cue position—to determine when cueing was effective within the trial sequence. This manipulation was done to determine which sort(s) of VSTM processes were influenced by dimension-based attention. The third aim was to determine whether the magnitude or character of dimensional attentional effects depends on the nature of the VSTM comparison task. It may be that the influence of dimensional cues is the same, irrespective of whether the task involves the detection of a change or a sameness event. However, there are a priori reasons to assume that this is not case. As we pointed out earlier, sameness detection is much harder than change detection, an asymmetry that reflects differences in the nature of the underlying VSTM comparison processes involved (Davis & Leow, 2005; Farell, 1985; Hyun et al., 2009). Thus, whereas change detection is supported by bottom-up guidance generated from an automatic comparison process, sameness detection is not. Instead, sameness detection must rely on active comparisons between the visual information held in memory and the current input from the test array to detect the critical event. Given this difference between change and sameness detection in terms of bottom-up guidance, it seems reasonable to expect that the tasks might also differ in their sensitivities to top-down direction given in the form of dimensional cues.

Experiment 1: Change detection

Method

Participants Twenty-two participants (20 female, two male) performed the experiment. All had normal or corrected-to-normal visual acuity and reported normal color vision.

Stimuli and procedure All stimuli were viewed in a darkened backlit room on a 16-in. Sony Trinitron CRT color monitor (1,024 × 768, 100 Hz) from an approximate distance of 1, 000 mm. The monitor was controlled by an Intel Pentium-4 PC fitted with an NVDIA GeForce 4 graphics card. The stimuli themselves consisted of outline geometric shapes; each was one of four types (with sizes given in visual angles at the viewing distance): equilateral triangle (1.3° height), cross (1° width × 1° height), ellipse (1.3° width × 1° height), and rectangle (1° width × 1.3° height). The line forming each shape was three pixels (0.2°) in width. The shapes were presented in one of four colors (luminance in cd/m^2 and CIE 1931 *x*, *y* coordinates, respectively, are given in parentheses): red (10.1; .448, .355), green (11.02; .259, .449), yellow (9.63; .467, .455), and blue (10.80; .199, .242). The shapes were presented on a neutral gray (34.99; .304, .350) background.

The experiment was conducted using bespoke software written in the BlitzMax programming language (version 1.5; Blitz Research Ltd., Auckland, New Zealand). A schematic depiction of the stimulus sequence on each trial is given in Fig. 1. Trials began with a brief alerting tone and the presentation of a fixation cross. This cross was shown alone for 600 ms, followed by the onset of the memory array. The memory array consisted of six shapes evenly spaced on a notional circle with a radius of 237 mm (13.5°) centered on the fixation cross. Combinations of shape and color were randomly selected for the individual stimuli in the memory array from the sample of four values for each dimension. This random selection was done with the constraint that at least two different color and shape values always appeared in the array. We used this limited number of stimulus values to ensure that verbal encoding processes were of limited use in performing the VSTM task. The memory array was presented for 600 ms, and was followed by a 600-ms blank ISI and then the test array, which was also presented for 600 ms.

On no-change trials, the test array was the same as the memory array. On change trials, the test array was the same as the memory array except that one feature value of one object was different. The different feature value was chosen randomly from the three other possible values for the dimension. For example, on a color change trial, a red triangle might became a blue triangle; on a shape change trial, a red triangle might became a red ellipse. A ratio of 5:1 change to no-change trials was given; color and shape change trials occurred with equal frequencies. This ratio was chosen on the assumption that cues would be most informative on change trials—since only here would the distinction between valid and invalid cues be meaningful.

After the test array offset, the fixation cross remained on screen until the participant had made a response. Participants responded by pressing one of two triggers on a joypad, according to whether or not they thought a change had occurred (the left trigger was designated for “no” responses, and the right trigger was designated for “yes” responses). Following a response, the fixation cross disappeared from the screen and immediate auditory feedback was given. A new trial was instigated after a 500-ms intertrial delay.

The dimensional cues were in the form of recorded speech enunciating the word “color” or “shape.” The speech was computer-generated but naturalistic. Sound files containing the speech were generated using online software

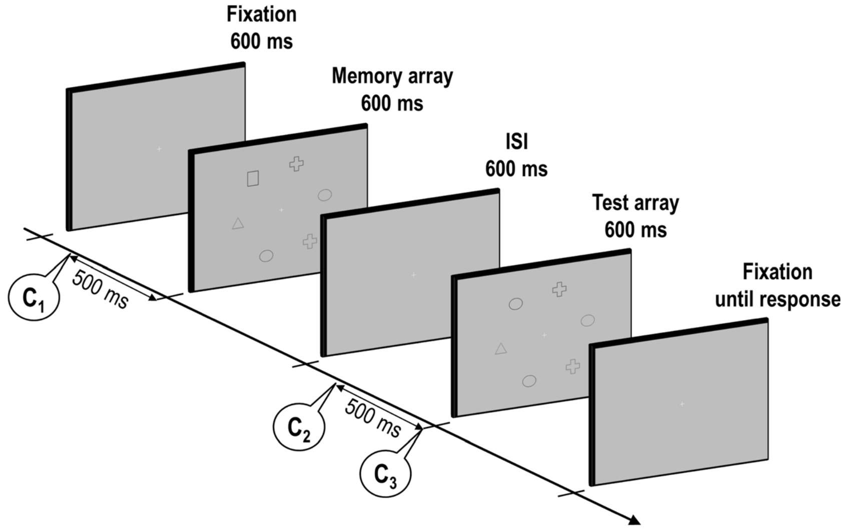

Fig. 1 Diagram of the trial sequence in Experiment 1. The three cue intervals (C_1, C_2, C_3) are indicated in the trial sequence; note that only one cue was ever given on any one trial. In the example (clockwise from the top), the memory array contains a green cross, blue circle, red cross, green circle, red triangle, and yellow rectangle. In the trial, the critical change event is present in the form of a shape change; in the test array all items are identical to those in the memory array, apart from the yellow rectangle becoming a yellow circle

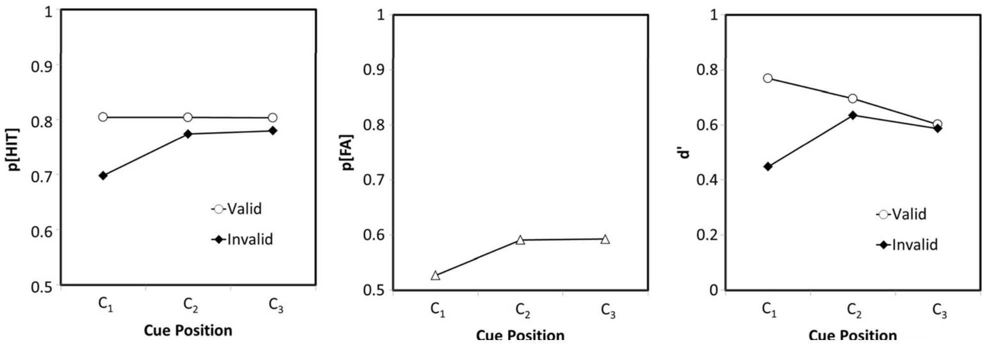

Fig. 2 Results from Experiment 1. The mean hit rates (p[HIT]) for valid and invalid trials are shown on the left; the mean false alarm rate (p[FA]) is in the middle; and the across-participant mean d' values for valid and invalid trials are on the right

(www.fromtexttospeech.com; we selected the British female voice "Rachel" with a "medium" speech rate). On change trials, cues stated the critical dimension with an 80 % validity; on no-change trials, the cue was randomly chosen to state either "color" or "shape," with the constraint that the two cue words occurred with equal frequencies. The cue was given at one of three intervals in the trial sequence: C_1, 500 ms before the onset of the memory array; C_2, 500 ms before the onset of the test array—that is, during the ISI; C_3, simultaneous with the onset of the test array. The cue appeared in each of the three intervals with the same frequency. All sounds were played through loudspeakers located at either side of the computer monitor.

Participants were informed about the validity of the cue and the ratio of change to no-change trials prior to the task. They were told to emphasize accuracy and not speed in their responding. The experiment consisted of 432 trials; before it started, participants were given a demonstration of the trial sequence and then performed 30 practice trials. During the experiment, a short break was given after every 48 trials.

Results

A signal detection analysis was performed on the data: Correct responses on change trials were designated as hits, and incorrect responses on no-change trials designated as false alarms. The hit rate—that is, the proportion of correct responses on change trials (p[hit])—was calculated separately for valid and invalid trials. From the hit and false alarm rates, d-prime (d') was calculated (d' is a response-bias-independent measure of sensitivity; see Macmillan & Creelman, 2005). The mean d' value for each of the six factorial combinations of conditions is shown in Fig. 2.

A 2 × 3 repeated measures analysis of variance (ANOVA) was performed on the d' scores. In this analysis, the two factors were Cue Validity (valid, invalid) and Cue Interval (C_1, C_2, C_3). A significant main effect was found for cue validity, $F(1, 21) = 5.48$, $MSE = .105$, $p = .029$, $\eta_p^2 = .207$, but not for cue interval, $F(2, 42) = 0.16$, $MSE = .387$, $p = .853$. The Cue Validity × Cue Interval interaction was also significant, $F(2, 42) = 3.295$, $MSE = .091$, $p = .047$, $\eta_p^2 = .136$.[3] To explore the interaction, paired-samples t tests were performed between valid- and invalid-cue trials separately for each of the three cue positions. These showed a significant effect of cue validity for cue position C_1 [$t(21) = 3.90$, $p < .001$], but not for C_2 [$t(21) = 0.59$, $p = .561$] or C_3 [$t(21) = 0.17$, $p = .871$]. As a further test, Bayes factors were calculated from the paired-samples t tests (see Rouder, Speckman, Sun, Morey, & Iverson, 2009; the default $r = 1$ was used in all calculations). For cue position C_1, the analysis confirmed evidence for a cueing effect at this interval (scaled JZS Bayes factor = 42.18, meaning that the data are over 40 times more probable under the alternative hypothesis—that the valid and invalid trials differ—than the null hypothesis). For intervals C_2 and C_3, the analysis supported the null hypothesis (for C_2, scaled JZS Bayes factor = 3.82; for C_3, scaled JZS Bayes factor = 4.43; this means that the null hypothesis was, respectively, nearly four times and more than four times more probable than the alternative hypothesis at these cue positions).

Discussion

The main effect of cue validity shows that the dimensional cues influenced the change detection sensitivity. This finding is consistent with previous reports of the effects of dimension-based attention on VSTM tasks (Pilling & Gellatly, 2013; van Lamsweerde & Beck, 2011). Our cue paradigm, by also varying the cue interval, gave some additional

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[3] A further analysis was also performed in which p[Hit] and p[FA] were calculated separately for color and shape change trials. This necessarily halved the number of trials per data point for the p[Hit] trials and meant that that standard deviations for the separate d's tended to be much larger, particularly for the (infrequent) invalid trials. Importantly, however, a three-way ANOVA (Cue Validity × Cue Interval × Change Type) showed that change type did not significantly interact with either of the other variables. Given this fact, and to maximize statistical power, the omnibus ANOVA is reported.

insight into the locus of dimension-based effects. Cues influenced change sensitivity when they were presented prior to the memory array, but they had no discernible effect when presented after this (during the ISI or with the test array). One interpretation of these results is that the dimension-based attentional influence is restricted to processes associated with encoding into VSTM. However, the reason may simply be, as we discussed earlier, that the later-presented cues do not convey enough benefit in the context of the change detection task for participants to utilize them. Thus, an influence on postencoding VSTM processes might be found in the context of a VSTM task with higher cognitive demands. We considered the sameness detection task one such candidate: The detection of sameness events seems to require a more active comparison process than does the detection of changes (Hyun et al., 2009). As a consequence of this fact, sameness detection might be more sensitive to the guidance given by top-down cues regarding the critical dimension. In Experiment 2, we tested this possibility.

Experiment 2: Sameness detection

Method

Participants There were 20 participants (12 female, eight male). These were sampled in the same manner and with the same exclusion criteria as for Experiment 1. No participant had taken part in the previous experiment.

Stimuli and procedure The same colored outline shapes described in Experiment 1 were used as stimuli, and the trial sequence was the same as in Experiment 1. However, in the test array, every item changed both its color and shape except on critical trials, in which one item retained one of its feature values (either its color or its shape) across the memory and test arrays. The new value for each feature was selected at random from the three other possible values for that feature dimension. A schematic depiction of the trial sequence in Experiment 2 is given in Fig. 3. Participants were instructed to report whether or not any item retained the same feature between the memory and test displays. Pilot work showed that performance was no better than chance when (as in Exp. 1) the displays contained six items; these pilot data further indicated that performance fell within the same range as in the change detection task when the set size was reduced from six to three items. Aside from these changes, the trial sequence was the same as in Experiment 1. A ratio of 5:1 sameness to no-sameness trials was chosen. On sameness trials the verbal cue indicated the critical dimension with an 80 % validity; on no-sameness trials the cue was random, with the constraint that the two words ("color" and "shape") were given with equal frequencies. Cues occurred equally often in each of the three positions, and auditory feedback was given immediately after the response. Demonstration examples were given to ensure that the task was understood. After the demonstration, each participant performed 30 practice trials before starting the main experiment.

Results

The same signal detection analysis was performed as we previously described for Experiment 1. The hit and false alarm rates and calculated d' values are reported in Fig. 4. A two-way repeated measures ANOVA (Cue Validity × Cue Interval) was performed on the d' scores. This analysis showed a significant main effect of cue validity, $F(1, 19) = 22.128$, $MSE = .249$, $p < .001$, $\eta_p^2 = .538$, but no effect of cue interval, $F(2, 38) = 2.171$, $MSE = .149$, $p = .128$. The Cue Validity × Cue Interval interaction was significant, $F(2, 38) = 3.881$, $MSE = .085$, $p = .029$, $\eta_p^2 = .170$.[4] Paired-samples t tests were performed between the valid and invalid trials. These showed a significant effect of cue validity at all three cue positions [C_1,$t(19) = 4.01$, $p < .001$; C_2, $t(19) = 4.45$, $p < .001$; C_3, $t(19) = 2.69$, $p < .05$]. A subsequent Bayes factor analysis of the t test results further confirmed the existence of cueing effects for all three cue positions (the scaled JZS Bayes factors for C_1, C_2, and C_3, respectively, were 47.05, 113.54, and 3.77; thus, in the most limiting case, C_3, the alternative hypothesis was almost four times more likely than the null).

Discussion

As we found with change detection, valid dimensional cues improved detection sensitivity. However, for sameness detection this effect was not restricted to the earliest cue position; the cues remained effective even when they were presented as late as with the onset of the test array.

General discussion

Our two experiments showed that dimensional cues influence VSTM performance: Sensitivity tended to be higher for both change detection and sameness detection when cues validly indicated the dimension for the critical event. The cue position manipulation exposed differences between the change and sameness detection tasks in terms of the locus of their effects. For change detection, the cues influenced sensitivity only when they were presented in the earliest cue position, before

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[4] As with Experiment 1, a further analysis was also performed in which scores were calculated separately for color and shape change trials. This again resulted in highly variable d' scores across participants. A three-way ANOVA demonstrated that change type did not significantly interact with the other two variables. For the same reasons discussed for Experiment 1, we report the omnibus ANOVA in these results.

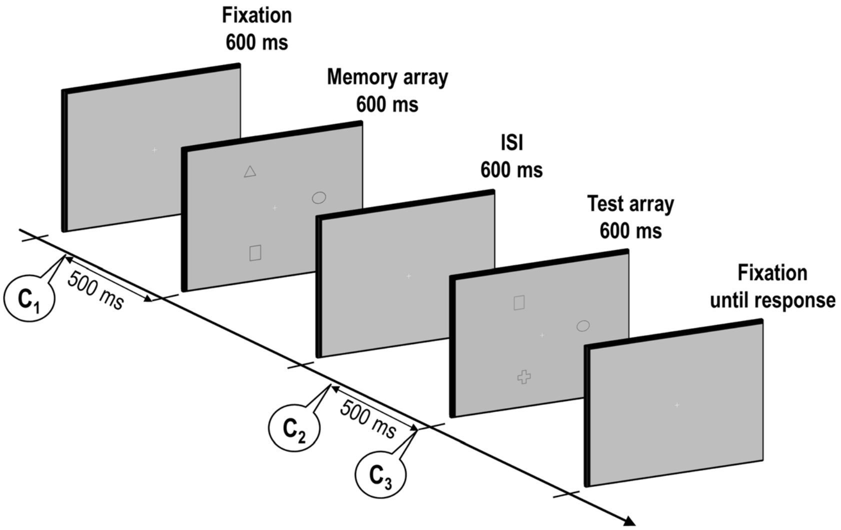

Fig. 3 Diagram of the trial sequence in Experiment 2. As with Experiment 1, the three cue intervals (C_1, C_2, C_3) are indicated in the sequence. Note that the memory and test arrays now include only three stimuli. In the memory array are (clockwise from the top) a green triangle, yellow circle, and green rectangle. In the test array, the three objects have changed: The green triangle has become a red rectangle, the yellow circle has become a green circle, and the green rectangle has become a blue cross. In the example, the critical sameness event is present; here it occurs on the shape dimension (the "circle" shape being retained in the second set of described objects)

the onset of the memory array. This fact suggests that the influence of dimension-based attention in this task was restricted to the encoding stages of VSTM. By contrast, for sameness detection, the cues influenced sensitivity at all three given positions. This shows that, in this task at least, dimension-based attention influenced encoding as well as later-stage VSTM processes.

We attribute these differences in cue effectiveness to the different manner in which change and sameness events are processed by the visual system. In a change detection task, any difference between an object's features and its representation in VSTM will generate a mismatch between memory and the current input. It has been shown that the occurrence of such a mismatch generates a bottom-up signal, which directs attention to the change (Hyun et al., 2009). Given this bottom-up guidance toward the change item, there may be little benefit to be obtained from being informed about the change dimension, in terms of the nature of the comparison process. Consequently, participants may simply ignore the cues (or otherwise fail to utilize them to actively modulate their attention) when these cues are presented after stimulus encoding.

For sameness events, the situation is different. Here no such reflexive mismatch signal is generated when a feature *does not* change. Because of this lack of bottom-up guidance, observers must rely on active comparisons between memory representations and the current input to detect the sameness event (Hyun et al., 2009). We suspect that the deliberative nature of the comparison process in sameness detection is what makes observers exhibit greater sensitivity to top-down influence. It should be noted that the specific implementation of the sameness detection task in Experiment 2 made the perceptual comparison process particularly challenging for the visual system. In most versions of the sameness detection paradigm, only one feature dimension is manipulated. For instance, in Davis and Leow (2005) participants had to detect

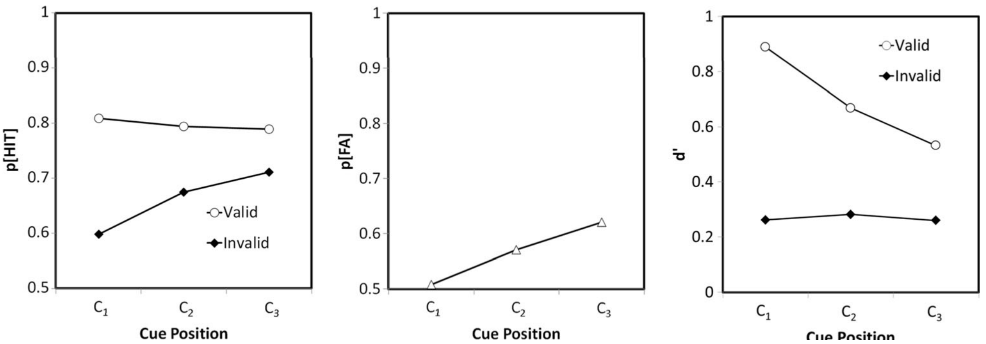

Fig. 4 Results from Experiment 2. The mean hit rates (p[HIT]) for valid and invalid trials are shown on the left; the mean false alarm rate (p[FA]) is in the middle; and the across-participant mean d' values for valid and invalid trials are on the right

the presence of a disk that remained constant in color across two displays when all other disks changed their color but not their shape. Thus, the variation in the display was always limited to values from a single feature dimension. In the present study, participants had to detect sameness in a *single feature* when variation in the display occurred across two feature dimensions. Thus, in our task the sameness item, like all of the other display items, was always physically different in some way across the two displays. To detect the sameness feature, the observer needed to deliberatively compare the feature values of the respective objects on each of the two possible dimensions. It is likely that the respective feature dimensions of objects can only be compared in a serial manner (Egeth, 1966; Sternberg, 1998). The cue information, therefore, could be used to prioritize the order in which the comparisons occurred in the two feature dimensions. When the cue was valid, this prioritization of the appropriate dimension might increase the likelihood of the critical sameness being identified before any time-based decay of the memory representations (van Lamsweerde & Beck, 2011).

The account above explains the effectiveness of cues at position C_2 in the sameness task; it does not so easily account for the cues' continued effectiveness at position C_3. Here the cue, by occurring simultaneously with the test array, gave no prior information to influence the comparison process. Instead, we suspect the main effect of this late cue was to influence the decision processes that occurred following any feature comparisons (Wilken & Ma, 2004; Yang, 2011). For instance, the cue might be used to weight evidence concerning the existence or absence of sameness toward that derived from the comparison process on the cued dimension. The effect of this weighting, when cues were valid, would be to reduce the amount of decision noise, leading to an increase in task sensitivity (Smith & Ratcliff, 2009).

Fundamentally, our results show how top-down knowledge about the feature dimension on which a defined perceptual event is likely to occur influences our sensitivity to that event. In this respect, our findings are similar to those reported in the context of pop-out search (e.g., Müller et al., 2003, Töllner et al. 2010), where it has been shown that a valid top-down cue that specifies the dimension on which a singleton is defined facilitates detection of that singleton. For instance, Müller et al. (2003) presented a verbal cue prior to the onset of a search display that specified an upcoming target dimension with 80 % validity. On valid trials, there was a clear benefit for reporting the singleton, in terms of both response times and accuracy. In this visual search literature, such dimensional effects have been largely attributed to the top-down control of early signal enhancement processes, which occur prior to any spatial selection operations (Found & Müller, 1996; Gramann et al., 2010; Töllner, Müller, & Zehetleitner, 2012). It is possible that early signal enhancement processes partly underlie the cue effects found on our two VSTM comparison tasks. Indeed, this signal enhancement could be the mechanism by which feature dimensions are prioritized during VSTM encoding; this difference in signal strength would determine the fidelity of the respective feature values in the subsequent memory representations. In the case of the change detection task, such sensory enhancement processes of the kind already reported in visual search might wholly explain the effects of dimensional cues. For the sameness detection task, however, as we earlier described, it seems that cues influence additional aspects of VSTM beyond the encoding stage.

As a final point, it should be noted that our results constitute evidence against a strong version of the integrated-object hypothesis (Luck & Vogel, 1997; Vogel et al., 2001; cf. Olson & Jiang, 2002). The results from both experiments indicated that objects in VSTM are not necessarily represented as complete entities; instead, what aspects of an object are represented seems to depend, at least in part, on the attentional state of the observer. What our cueing manipulations seem to show is how the limited capacity and processing resources of VSTM can be prioritized by the visual system in a flexible manner to meet the observer's current goals. Indeed, previous work has similarly claimed that the feature contents of VSTM can vary according to top-down-directed goals (Burmester & Wallis, 2011; Davis & Holmes, 2005; Droll et al., 2005). Our results suggest, at least in the case of sameness detection, that this top-down influence is not just limited to how objects are initially represented, but may also extend to later feature comparison and decision processes associated with these representations. Further research will be needed to more precisely elucidate the mechanisms involved in these different sorts of dimension-based attentional influences on VSTM processes.

Author note These findings were presented in provisional form at the European Conference of Visual Perception 2014 (Belgrade, Serbia) and at the British Psychological Society, Cognitive Section, Annual Conference in 2014 (Nottingham, UK). We thank two anonymous reviewers for their detailed comments on an earlier version of the manuscript.

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