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Splitting attention across the two visual fields in visual short-term memory

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Abstract

Humans have the ability to attentionally select the most relevant visual information from their extrapersonal world and to retain it in a temporary buffer, known as visual short-term memory (VSTM). Research suggests that at least two non-contiguous items can be selected simultaneously when they are distributed across the two visual hemifields. In two experiments, we show that attention can also be split between the left and right sides of internal representations held in VSTM. Participants were asked to remember several colors, while cues presented during the delay instructed them to orient their attention to a subset of memorized colors. Experiment 1 revealed that orienting attention to one or two colors strengthened equally participants' memory for those colors, but only when they were from separate hemifields. Experiment 2 showed that in the absence of attentional cues the distribution of the items in the visual field per se had no effect on memory. These findings strongly suggest the existence of independent attentional resources in the two hemifields for selecting and/or consolidating information in VSTM.

The ability to maintain visual information in an accessible state is a critical aspect of our cognitive capacities as it allows us to interact successfully in the visuo-spatial world. Because our visual short-term retention system (i.e., visual short-term memory - VSTM) is extremely limited in storage capacity (Luck & Vogel, 1997), only a subset of information from our extrapersonal world can be transferred into this limited memory space at any one time. The selection of this subset of information is made by attentional mechanisms that can be voluntarily or involuntarily oriented to particular locations or objects. For example, when spatial attention is cued to a particular location of the visual field, the object that occurs at that location will be more likely transferred into VSTM as compared to the other objects (Makovski & Jiang, 2007; Schmidt, Vogel, Woodman, & Luck, 2002).

During the last 10 years, an increasing number of studies have revealed that once transferred into VSTM, the internal representations remain highly flexible and can be selectively accessed and consolidated by attentional mechanisms (e.g., Delvenne, Cleeremans, & Laloyaux, 2010; Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura, Luck, & Vecera, 2007; Nobre, Coull, Maquet, Frith, Vandenberghe, & Mesulam, 2004). Those studies use the *retro-cuing paradigm*, in which an attentional orienting cue was presented during the retention interval of a memory task and pointed to the location of one of the items held in VSTM. Memory for the cued item is found to be better as compared to memory for the uncued items. This finding is crucial as it suggests that it is possible to orient spatial attention onto a subset of internal representations beyond the phase of perceptual encoding. Because spatial location plays a central role in the maintenance of objects in memory (e.g., Jiang, Olson, & Chun, 2000), directing attention to one location previously occupied by an object helps solidify and/or retrieve that object from memory. However, this ability to attentionally select locations already held in VSTM appears to be more constrained than orienting attention in perception. In a recent study, Makovski and Jiang (2007) directly compared the effect of orienting attention to multiple locations before (pre-cuing) and after (retro-cuing) the appearance of a memory array. They found that while up to three attentional cues could be used effectively when presented before the memory array, only a single cue was advantageous for memory performance when presented after the offset of the memory array. Although this, along with previous studies (Awh & Pashler, 2000; Kraft, Müller, Hagendorf, Schira, Dick, Fendrich, & Brandt, 2004; Kramer & Haln, 1995), indicates that spatial attention can be oriented onto multiple locations at once in perception, Makovski and Jiang's study suggests that orienting attention in memory may be restricted to a single location.

Here, we report an exception to this restriction. We show that attention can be split in VSTM between the left and right visual fields. Specifically, the present study reveals that two non-contiguous locations can be selected from VSTM at no extra cost as compared to a single location, but only if they are from separate hemifields. Past work has demonstrated that attention can be split in perceptual space between the two hemifields at a lower cost as compared to within the same hemifield. This has been observed in a number of visual tasks, such as tracking objects (Alvarez & Cavanagh, 2005), remembering spatial locations (Delvenne, 2005) and orientations (Umemoto, Drew, Ester, & Awh, 2010), matching stimuli (Kraft et al., 2004; Sereno & Kosslyn, 1991), enumerating objects (Delvenne, Castronovo, Demeyere, & Humphreys, 2011), and identifying targets (Awh & Pashler, 2000), amongst others. In particular, performance at those tasks was better when the to-be-attended items were distributed across the left and right visual fields as when they were all displayed within the same hemifield. Here, we provide the first evidence that attention can also be split beyond perception, namely between the left and right sides of internal representations.

Experiment 1

Method

Sixteen volunteers took part in this experiment (9 women; mean age = 21.4, range 20 – 24 years). In all experiments, the participants had normal (self-reported) or corrected-to-normal visual acuity and normal color vision. They were tested individually in a quiet room with dim lighting.

Visual stimuli were generated by a 3.00 GHz PC and displayed on a 17” screen. The script was generated by E-Prime programming software (Psychology Software Tools, Inc., www.pstnet.com) and responses were collected using the computer keyboard. Six highly discriminative colored squares (blue, green, pink, red, turquoise, and yellow), produced by permutation of the presence or absence of red, green and blue phosphors, were used as stimuli. At a viewing distance of approximately 60 cm, each square subtended a visual angle of 0.76° x 0.76°. The stimuli were randomly located equidistantly at eight different possible positions on an imaginary circle (7.12° in diameter) centered at fixation. The eight locations were 12:45, 2:15, 3:45, 5:15, 6:45, 8:15, 9:45, and 11:15 o’clock locations. The colors were selected at random with the constraint that two contiguous colors could not repeat. A gray background was used to reduce afterimages.

On each trial, participants were first presented with an initial central fixation cross that they had to fixate throughout the entire trial. After 800 ms, the memory array was presented for 150 ms, followed by a 1,000 ms blank interval, then by a cue array for 50 ms, followed by another 1,000 ms blank interval and finally by the probe that remained present until a response key was pressed. There were three retro-cue conditions. In the *one-cue condition*, the cue array consisted of a single cue (i.e., a white outlined square subtending 0.76° x 0.76°) randomly positioned at one of the eight locations. In the *bilateral-cues condition*, the cue array consisted of two non-contiguous cues located in opposite hemifields. In the *unilateral-cues condition*, the two non-contiguous cues were located within the same hemifield. The distance between the cues was kept constant in both the *bilateral-* and *unilateral-cues conditions* and they were always separated by an uncued location. The cue(s) indicated the location of the test probe (validity = 100%). To measure the effect of retro-cuing on memory capacity, a fourth condition was used in which no cue was presented. In this *no-cue condition*, the memory array was presented for 150 ms, followed by a 1,000 ms blank interval and then immediately by the probe. Figure 1 illustrates the four conditions. Participants were instructed to indicate whether the test color was the same as, or different from the one that was located at the same position on the memory array (with 50% probability). The next trial was automatically initiated 500 ms later.

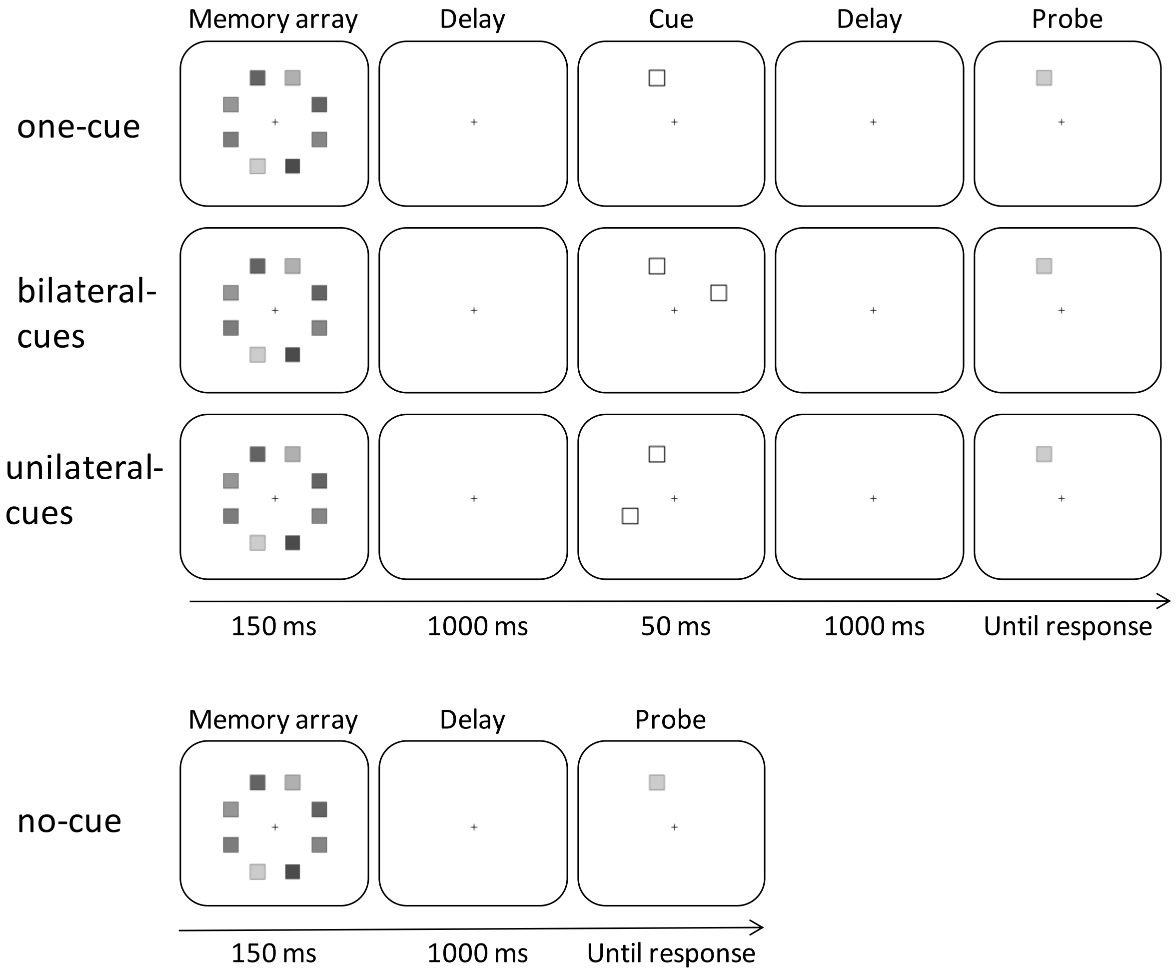

Fig. 1. Illustrations of the four conditions and the sequence of events in Experiment 1. The different gray levels represent different colors.

The conditions were randomly mixed during the experiment and there were a total of 48 trials in each condition. The whole experiment consisted of 192 experimental trials, evenly divided into six 32-trial blocks. Each block began with the presentation of three digits that participants were required to repeat aloud as quickly as they could throughout the block. This concurrent articulatory suppression task was used to discouraged participants from verbally recoding the visual information (Baddeley, 1986).

Results and discussion

We computed A’ from signal detection theory (Aaronson & Watts, 1987; Grier, 1971; Pollack & Norman, 1964) to assess the accuracy of the memory performance for each condition and for each participant. To obtain a second representation of the results, we also measured Cowan’s K (Cowan, 2001), an estimation of memory capacity. Figures 2a and 2b show the A’ and K values, respectively, in each condition. Because the analyses on K produced the same pattern of statistical significance as A’, we report only the statistical results on the A’ values. The ANOVA (repeated measures) on accuracy (A’) revealed a main effect of condition, $F(3, 45) = 4.25$, $MSE = 0.007$, $p < .01$. Pairwise comparisons showed no difference between the *one-cue* and *bilateral-cues conditions* ($p = .60$) and no difference between the *unilateral-cues* and *no-cue conditions* ($p = .84$). However, both the *one-cue* and *bilateral-cues conditions* were significantly better performed ($p < .05$) than the *unilateral-cues* and *no-cue conditions*. In addition, no difference was found between the left and right visual fields ($p = .30$) and between the upper and lower visual fields ($p = .60$). Finally, we compared change detection performance between items near the vertical meridian (i.e., the 12:45, 5:15, 6:45, and 11:15 o’clock locations) and items farther away (i.e., the 2:15, 3:45, 8:15, and 9:45 o’clock locations). The paired t-test revealed no effect of distance of the items relative to the vertical meridian ($p = .11$).

Those results show that two items can be attentionally selected from, and/or consolidated in VSTM at no extra cost compared to a single memory item, provided that the two items were bilaterally presented in the memory array. In contrast, when the two memory items came from the same single hemifield, the retro-cuing effect disappeared. This finding strongly suggests that attention can be split in VSTM between the left and right sides of internal representations[1].

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[1] The two retro cues were somewhat horizontally aligned in the *bilateral-cues condition* and vertically aligned in the *unilateral-cues condition*. To ensure that the bilateral advantage does not simply reflects an advantage of the horizontal orientation rather than a true benefit of splitting attention between the two hemifields, we conducted another experiment, with 16 participants, in which the items shifted 6° to the left or right of

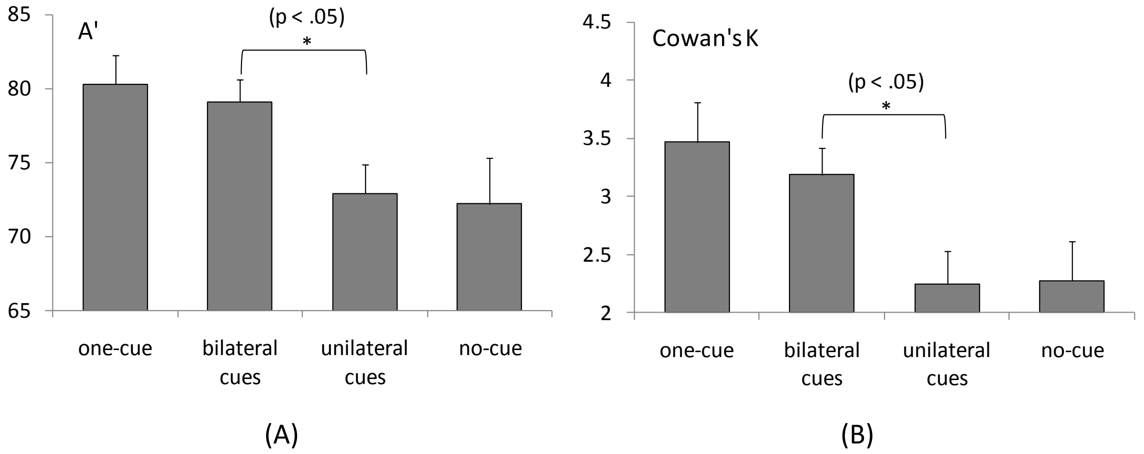

Fig. 2. Results (A' and Cowan's K) of Experiment 1. Error bars represent standard errors of the mean values.

Experiment 2

Previous research has shown that short-term memory for spatial information, such as locations (Delvenne, 2005) and orientations (Umemoto et al., 2010) is better across hemifields than within a single one. Given that VSTM is contralaterally organized (Eimer & Kiss, 2009; Gratton et al., 1997), remembering visual items that occur in separate hemifields may indeed be easier as compared to within the same hemifield because they are registered in different hemispheres. Although this bilateral advantage has never been found in memory for non-spatial features such as colors (Delvenne, 2005; Delvenne, Kaddour, & Castronovo, 2011; see also Umemoto et al., 2010, p. 78), the possibility remains that the retro-cues in Experiment 1 were simply facilitating a natural advantage when items are distributed in the two hemifields. In experiment 2, we examined whether the beneficial effect of the bilateral presentation of the retro-cues might be explained by a general cross-hemifield advantage in VSTM.

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fixation so that all the colors, and both the horizontally and vertically aligned retro cues, always occur within a single hemifield (see Alvarez & Cavanagh, 2005; Delvenne et al., 2011a, for a similar procedure). The results revealed no effect of hemifield (p = .83), no effect of the orientation of the cues (p = .69) and no interaction (p = .61). The absence of a horizontal advantage strongly suggests that the bilateral benefit observed in the present study cannot be explained by the somewhat horizontal alignment of the cues in the *bilateral-cues condition*.

Method

Sixteen new participants (11 women), aged between 19 and 37 years (mean = 24.5) took part in this experiment, which replicated Experiment 1 with the following changes: (i) the display consisted of four invisible quadrants (subtending 3.8° x 3.8° each) placed around the central fixation cross and separated vertically and horizontally (centre-to-centre) by 4°; (ii) as shown in Figure 3, eight colors were located at each corner of two of the four quadrants, either from the same hemifield (*unilateral display* – upper-left/lower left or upper-right/lower-right) or from different hemifields (*bilateral display* – upper-left/upper-right or lower-left/lower-right); (iii) the colors within one quadrant could not repeat; (iv) there were two conditions: in the *two-cues condition*, the cue array consisted of two non-contiguous cues located equidistantly in distinct quadrants, while in the *no-cue condition*, the probe immediately followed the first blank interval. The experiment consisted of 256 trials (i.e., 2 conditions X 2 displays X 64 trials), divided into eight 32-trial blocks.

Results and discussion

The 2 (conditions: no-cue/two-cues) x 2 (displays: unilateral/bilateral) ANOVA (repeated measures) on accuracy (A') revealed no effect of condition ($p = .148$) and no effect of display ($p = .104$). However, there was a significant interaction between those factors, $F(1, 15) = 6.35$, $MSE = 0.024$, $p < .03$ (see Figure 4). The interaction revealed a bilateral advantage in the *two-cue condition* only ($p < .014$). Finally, no difference was found between the left and right visual fields ($p = .51$) and between the upper and lower visual fields ($p = .32$). The absence of a bilateral advantage in the no-cue condition suggests that the retro-cues effect cannot be accounted for by a general cross-hemifield advantage in VSTM. Rather, these findings indicate an advantage of splitting attention between hemifields within internal representations.

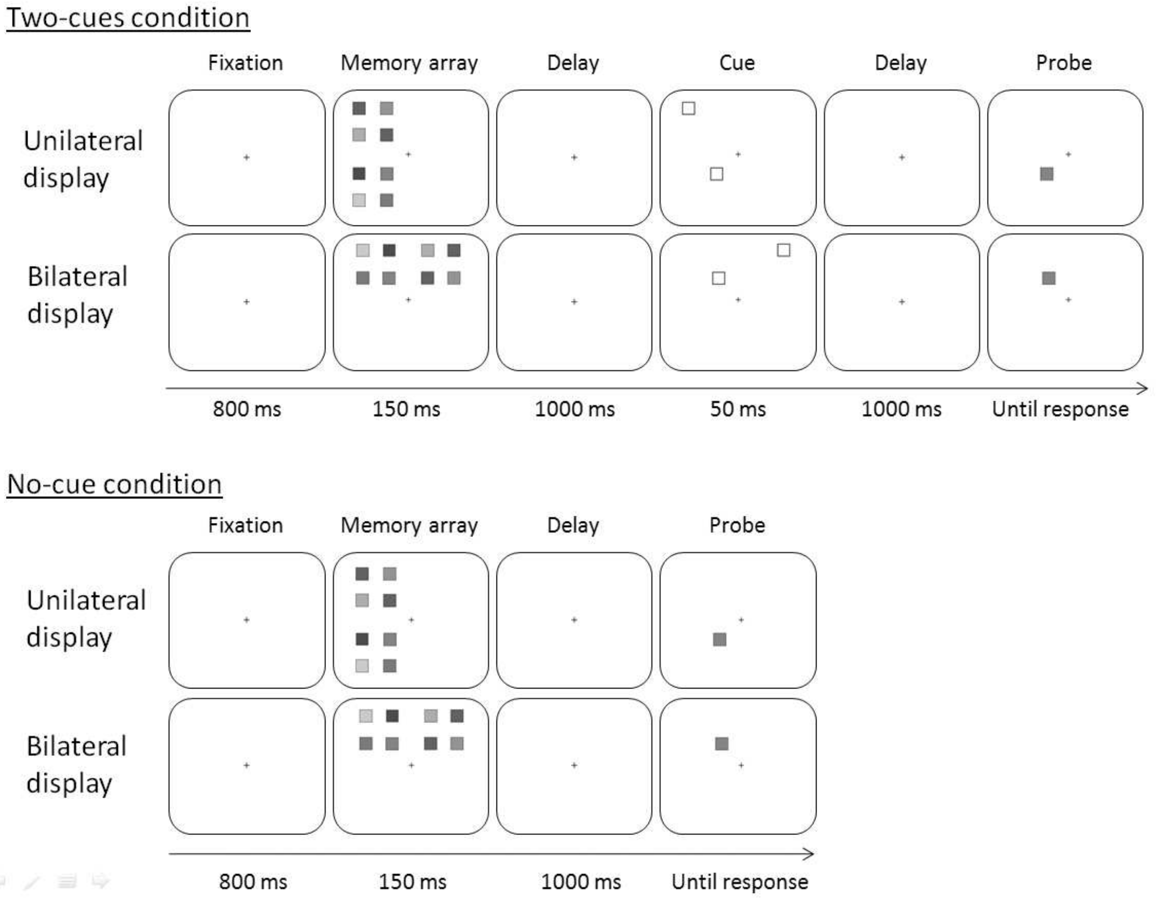

Fig. 3. Illustrations of the different conditions and the sequence of events in Experiment 2. The different gray levels represent different colors.

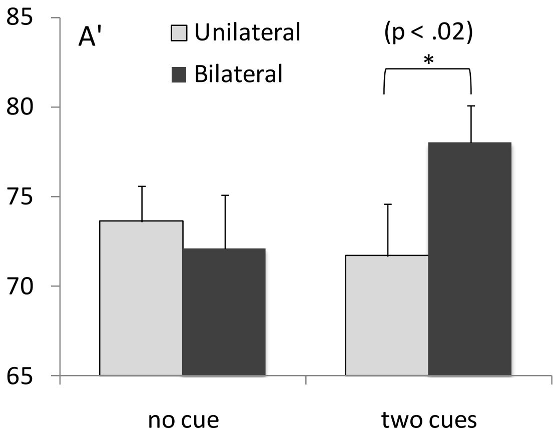

Fig. 4. Results (A') of Experiment 2. Error bars represent standard errors of the mean values.

General Discussion

In this study, we used the retro-cuing paradigm to test whether attention can be divided over two non-contiguous items held in VSTM beyond the phase of perceptual encoding. Recent studies have shown that attention can be selectively oriented to a particular item in VSTM (e.g., Delvenne et al., 2010; Griffin & Nobre, 2003; Landman et al., 2003; Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007; Nobre et al., 2004). Here, we show that attention can be oriented to two items in VSTM at no extra cost compared to a single item. Furthermore, although attention may have multiple foci within VSTM, the efficiency of these foci depends on their distribution in the visual field. When two retro-cues were distributed in separate hemifields, they provided the same benefit on memory performance as a single retro-cue. In contrast, no performance benefit was found when the two retro-cues occurred within the same single hemifield. This bilateral advantage cannot be explained by a general cross-hemifield advantage in VSTM (Experiment 2). Rather, these findings suggest that attention can be split in VSTM between the left and right sides of internal representations.

Several explanations can be proposed to account for the ability to split attention across hemifields in VSTM. One possibility is that the items selected from VSTM by the retro-cues are integrated to form a global shape. One must then assume that grouping multiple items together is easier when the items are located in separate hemifields than when they are from the same hemifield. However, our view is that this is unlikely to be the case in the present study. Firstly, the nature of the stimuli used here (i.e., colors) would make such a grouping process difficult: (i) no gestalt principles, such as similarities or symmetries for instance, that would encourage grouping, can be found in the displays that were used; (ii) previous studies have demonstrated that grouping features that belong to the same dimension, like colors, has no effect on memory for those features (e.g., Delvenne & Bruyer, 2004; Delvenne & Dent, 2008; Xu, 2002; Wheeler & Treisman, 2002). Secondly, past research has revealed that within-hemifield integration precedes and is more efficient than across-hemifield integration (Humphreys, Cinel, Wolfe, Olson, & Klempen, 2000; Large, Culham, Kuchinad, Aldcroft, & Volis, 2008; Pillow & Rubin, 2002). Thus, even if the cued colors were somewhat grouped together in VSTM, this cannot explain the bilateral advantage observed here.

Another possibility is that attention can only be oriented to one location at a time in VSTM and cycles rapidly through the other locations. According to this account, a bilateral advantage would be observed if reorienting attention across hemifields in VSTM is easier or faster than reorienting attention within the same hemifield. However, this is not compatible with past evidence showing that it actually takes more time to shift attention from one hemifield to the other than within the same hemifield (Hughes & Zimba, 1987; Ibos, Duhamel, & Ben Hamed, 2009). In addition, Griffin and Nobre (2003) have shown that when attention is focused on one memory item, memory for the other unattended items deteriorates. Therefore, if attention shifts from one location to another in VSTM, memory performance should decline as a function of the number of shifts required. Against this, we observed that orienting attention to either one or two bilateral items consolidated evenly participants' memory for those items.

The more plausible account for the present data appears therefore to be the existence of somewhat independent attentional resources in the left and right hemispheres for selecting and/or consolidating information in VSTM. Previous studies on healthy and brain-damaged patients have suggested that each hemisphere has its own independent attentional resources (Alvarez & Cavanagh, 2005; Kinsbourne, 1987; LaBerge & Brown, 1989; Luck, Hillyard, Mangun, & Gazzaniga, 1989). Given that the selection of information in memory may be based on similar mechanisms, and may recruit similar cortical regions as the selection of information in perceptual space (Griffin & Nobre, 2003; Nobre et al., 2004), we propose that each hemisphere-specific pool of attentional resources can still operate independently on the representations stored in VSTM beyond the phase of perceptual encoding. Splitting attention between the left and right sides of internal representations is possible because both hemispheres can contribute resources.

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