

# Double Take: Parallel Processing by the Cerebral Hemispheres Reduces the Attentional Blink

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Recent data have shown that parallel processing by the cerebral hemispheres can expand the capacity of visual working memory for spatial locations (J. F. Delvenne, 2005) and attentional tracking (G. A. Alvarez & P. Cavanagh, 2005). Evidence that parallel processing by the cerebral hemispheres can improve item identification has remained elusive. The authors used a novel variant of the attentional blink paradigm to show that the attentional blink is reduced if targets are divided between the hemispheres rather than directed to a single hemisphere. Parallel processing by the cerebral hemispheres can thus expand the capacity of processes involved in item identification. The authors also show that prior engagement of the attentional system may compromise the processing of items directed to the right visual field. This pseudoextinction may explain the failures of previous attempts to demonstrate that parallel processing can improve item identification (J. F. Delvenne, 2005; S. J. Luck, S. A. Hillyard, G. R. Mangun, & M. S. Gazzaniga, 1989).

*Keywords:* attentional blink, laterality, interhemispheric interaction, perceptual selection

Within any visual scene, there is far more information than people can consciously perceive. Conscious perception of items requires attention, which is generally acknowledged to be capacity limited. Because visual attention is not infinitely expandable, the efficiency with which attentional capacity is allocated is a critical determinant of the amount and quality of the information of which an individual will be aware.

Item identification capacity can be maximized by directing items of interest to somewhat distinct or independent neural mechanisms (e.g., Boles & Law, 1998; Friedman & Polson, 1981; Wickens & Sandry, 1982). Potter, Chun, Banks, & Muckenhoupt (1998) used the attentional blink (AB)—both the name of a particular rapid serial visual presentation (RSVP) paradigm and

the name of the phenomenon produced by that paradigm—to demonstrate this enhanced capacity. They found that visual targets preceded closely in time by other visual targets were less likely to be correctly identified than those preceded by auditory targets. They concluded that impaired target detection in the visual–visual condition was due to a bottleneck in visual processing that delays (and consequently compromises) processing of the second target. If the initial target was presented to the auditory system, however, no such delay ensued. In other words, targets were more likely to be available for conscious report if they were processed by different neural mechanisms than if they were processed by the same neural mechanisms. Although the AB is sometimes found between modalities (Arnell & Jolicoeur, 1999; Arnell & Larson, 2002; Jolicoeur, 1999), it is usually smaller than that found within the visual modality (Arnell & Larson, 2002) unless it also reflects task-switching demands (see Chun & Potter, 2001, for a review of this issue). These findings indicate that item identification capacity may be most efficiently exploited if different perceptual processing mechanisms are used to process the items of interest.

In the present study, we investigated whether item identification capacity within a sensory system might benefit from a similar exploitation of separable neural processors. Specifically, we investigated whether the relatively independent processing resources of the cerebral hemispheres could be used to expand the efficiency with which items are identified. Previous reports of the hemispheres' improving working memory and attentional capacity through parallel processing have surmised that their independent resources cannot be used to improve the efficiency of item identification (Alvarez & Cavanagh, 2005; Delvenne, 2005). Although dividing task-relevant items between the hemispheres increases the number of items whose motion may be tracked (Alvarez & Ca-

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vanagh, 2005) and whose locations may be held in visual short-term memory (Delvenne, 2005), it does not increase the number of colors that may be held in visual short-term memory (Delvenne, 2005) or the efficiency of a conjunction search (Luck et al., 1989).

The vast body of research by Banich and colleagues provides good reason to suspect that the hemispheres may be able to perform item identification processes in parallel (Banich, 1998; Banich & Belger, 1990; Belger & Banich, 1992; Weissman & Banich, 2000). Their data suggest that attentional capacity may be more efficiently exploited if both hemispheres are required to participate in the performance of an item-matching task. One explanation for these results may be that when matching items are divided between the hemispheres, they can be identified in parallel (Banich, 1998). When the demands of the matching task are sufficiently high, the benefits of parallel processing outweigh the costs of integrating information about the match decision between the hemispheres. When asked to determine whether a lowercase target letter has the same name as one of two capital probe letters, participants are faster if the matching items are directed to opposite hemispheres (Banich, 1998; Banich & Belger, 1990; Belger & Banich, 1992). Dividing targets between the hemispheres also improves participants' performance at matching shapes of different colors (Banich, 1998) or global-local stimuli that are inconsistent on the task-irrelevant dimensions (Weissman & Banich, 1999). Of note, these effects are only observed when the attentional demand of the task is relatively high. If asked to determine whether either of two probe items are physically identical to a single target item, participants actually show better performance if the matching pair of items is directed to a single hemisphere (Banich, 1998; Banich & Belger, 1990; Belger & Banich, 1992; Passarotti, Banich, Sood, & Wang, 2002; Weissman & Banich, 1999, 2000; Weissman, Banich, & Puente, 2000). If the number of probe items is increased to four, however, match decisions about physically identical stimuli are also facilitated when the matching items are divided between the hemispheres (Belger & Banich, 1992). When items must be identified and compared, then, dividing targets between the hemispheres improves task performance. One possible explanation for these results is that dividing matching target items between the hemispheres allow them to be identified in parallel (Banich, 1998).

In the current series of experiments, we used the AB paradigm to investigate whether dividing targets between the hemispheres can improve the efficiency with which they are identified and whether such improvement is tied to the difficulty of target selection. In AB tasks, participants are presented with an RSVP stream, so defined because sequentially presented visual items are individually displayed for a very brief period (about 100 ms). Participants are typically asked to identify or detect two targets embedded within a series of distractor items. Targets and distractors may be differentiated by category (such as letters among numbers), physical properties (red items among green items), or by their identity (an X among other letters). If the first target item (T1) is correctly identified, the second target item (T2) is unlikely to be identified if it follows T1 within 200–500 ms (Raymond, Shapiro, & Arnell, 1992, 1995; Shapiro, Raymond, & Arnell, 1994). This deficit is called the *AB*.

Initial investigations of the AB effect concentrated on elucidating the conditions that were necessary and sufficient to produce it; the conclusion of these investigations is that the AB represents

capacity limitations in a late-stage process involved in the generation or maintenance of representations that ultimately guide response processes. First of all, T1 must receive attention in order for an AB to result. If T1 is present in the RSVP stream but participants do not direct attention to it, T2 report is unimpaired (Raymond et al., 1992, 1995; Shapiro et al., 1994). This finding indicates that the process indexed by the AB is specific to attended items. Second, T1 must be followed or accompanied by interfering information (Marois, Chun, & Gore, 2000; Raymond et al., 1992, 1995; Seiffert & Di Lollo, 1997). This information may be in the form of a perceptually confusing stimulus, such as a metacontrast mask (Seiffert & Di Lollo, 1997) or may be a distractor, a non-target visual item (Raymond et al., 1995). In the absence of such interference, such as if a blank interval follows T1, T2 is reported as accurately as T1. This indicates that the process indexed by the AB must be involved in generating, maintaining, or operating on a representation of the target item that is segregated from that of the distractor item. If this were not the case, an AB would occur even when T1 was followed by a blank interval (Raymond et al., 1992). Finally, either the selection or maintenance of information from T2 must be disrupted. This disruption may come in the form of an interruption mask that overwrites the signal of the potential targets in early visual processing regions (Giesbrecht & Di Lollo, 1998) or in the form of a switch in the location or defining feature of the T2 that prevents its selection (Kawahara, Di Lollo, & Enns, 2001). The temporally limited process indexed by the AB, therefore, must occur at some late stage of visual processing. For T2 to be accurately reported in the absence of a trailing mask (assuming that a switch in the location or defining feature of the targets has not prevented it from being selected), some visual processors must be able to maintain a representation of T2 until later-stage processors are free to process it. Together, these requirements indicate that the AB results from inadequate attentional capacity in the processes that generate or maintain representations that guide response processes. These capacity limitations introduce a delay of processing that may prevent early visual representations of subsequent items from being formed and/or leave such representations vulnerable to interference from nontargets.

In the following series of experiments, we used the AB paradigm to investigate whether dividing targets between the hemispheres can increase the likelihood that they will be reported and to determine the extent to which such benefits are driven by the relative contribution of selection demands to the AB effect.

## Experiment 1

We used a novel variant of the standard AB paradigm that enabled us to either direct the two targets to a single hemisphere or divide them between the hemispheres. The participants' task was to identify the two targets (i.e., letters) interspersed among distractors (i.e., numbers). Although the earliest investigations of the AB used a dual-task paradigm in which participants were asked to first identify a T1 letter, then detect T2 (often an X), these paradigms necessitate the inclusion of control trials in which only the T2 task is performed. These control trials allow the impact of T1 processing on T2 detection to be established but double the number of trials participants must perform. In order to avoid making our experiments prohibitively long, we used an "identify and identify" task in which participants are asked to identify two letters that

appear among distractor items (Chun & Potter, 1995). In this version of the AB task, performance on the T1 item serves as the control for performance of the T2 item.

The traditional presentation of a single stream of items to central vision did not allow us to control the hemispheres that receive the target items. To do so, we needed to position individual targets within a single visual field. We therefore created a novel four-item AB paradigm in which four RSVP streams occurred simultaneously, one in each quadrant of the visual field (see Banich & Shenker, 1994, for a review of the rationale for keeping load balanced between the hemispheres across conditions). In our version of the AB paradigm, the two target letters were never presented in the same spatial location (Dell'Acqua, Pascali, Jolicœur, & Sessa, 2003; Raymond et al., 1995; Visser, Bischof, & Di Lollo, 1999; Visser, Zuvic, Bischof, & Di Lollo, 1999). Instead, T2 could be presented to the same hemisphere as T1 (but to the other stream in that visual field) or could appear in one of the streams in the opposite visual field. If the cerebral hemispheres can perform visual item identification in parallel, directing the two targets to opposite hemispheres should allow one hemisphere to process T1 while the other processes T2. This should result in a reduction in the AB for these trials relative to those in which both T1 and T2 are processed by the same hemisphere.

### Method

**Participants.** We tested 24 right-handed, neurologically intact individuals who were between 18 and 30 years of age. We used a questionnaire to determine participants' handedness; individuals were considered right-handed if they wrote with their right hand and performed simple tasks, such as hammering a nail or brushing their teeth, with their right hand more than 85% of the time. All participants had normal or corrected-to-normal vision; we also determined that each participant had normal lateral phoria. (Abnormal lateral phoria, or relative eye position, can cause the eyes

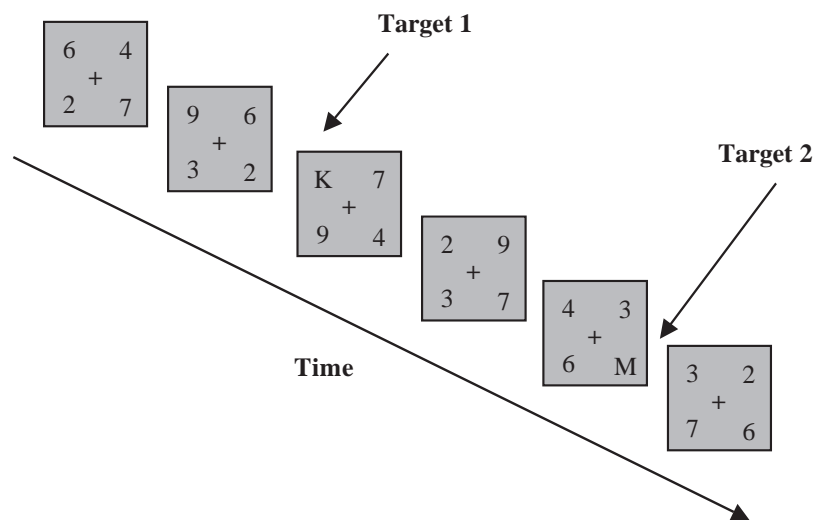
to focus in different locations, thus invalidating our assumptions about which hemisphere initially receives tachistoscopically presented information.) Participants who did not meet the criteria for normal vision were excused from the experiment. Participants were students at the University of Illinois at Urbana-Champaign and were paid \$6 per hour, or received class credit, for their participation.

**Stimuli.** We used the letters A, B, C, D, E, G, H, J, K, L, M, N, P, R, T, U, V, W, X, and Y as target stimuli. Letters were randomly selected, but the same letter never served as a target twice in the same trial. The numbers 2, 3, 4, 6, 7, 8, and 9 were used as distractor items. Letters and numbers were presented in 22-point bold Chicago font.

**Display.** One item was located in each quadrant of the visual field. Each item was centered 2° of visual angle lateral and vertical from fixation (see Figure 1). A fixation cross that varied in color and size also appeared with each group of task-relevant items. Pilot work indicated that participants found it easier to remain fixated on the cross if it changed color and size. We refer to each group of task-relevant items and a fixation cross as a *frame*.

Participants performed a block of 20 practice trials and three blocks of 144 test trials. Trial onset was signaled by a blinking fixation cross. Eleven to 15 frames followed the last fixation cross. Each frame was displayed for 80 ms. Frames were separated by a 20-ms interstimulus interval. In order to measure the duration of the AB, we varied the lag, or number of frames by which T2 followed T1, from one to six. At the end of each trial, participants were prompted to indicate, via keypress, the identity of the two letters that had appeared among the randomly selected numbers in the trial. After a 500-ms intertrial interval, a new trial began.

To manipulate the hemispheres that received T1 and T2, we varied the spatial locations at which the two letters appeared. T1 was equally likely to occur in any of the four positions: top right visual field, bottom right visual field, top left visual field, or



**Figure 1.** Each display in the rapid serial visual presentation (RSVP) sequence contained four items and a fixation cross. Each display lasted 80 ms; displays were separated by a 20-ms interstimulus interval. Two uppercase letters (in this case, M and K) were present in every stream of displays; the participant's task was to identify both targets letters after presentation of the RSVP stream was completed.

bottom left visual field. After T1 appeared, T2 was equally likely to appear in either the same visual field as T1 or in the opposite visual field, but it never appeared in the same spatial location as T1. If T2 appeared in the opposite visual field, it was equally likely to appear in either the top or bottom location. T1 and T2 were therefore equally likely to appear in the right or left visual field, and equally likely to occur in the same or opposite visual fields. This arrangement required participants to shift attention across a greater average distance on trials in which targets were divided between the cerebral hemisphere than on trials in which targets were directed to the same hemisphere.

One alternative arrangement would have been to include only divided hemisphere trials in which attention was shifted horizontally and within-hemisphere trials in which attention was shifted only vertically. We decided against using this method because we thought it was possible that shifting attention horizontally might be easier than shifting attention vertically. If this were the case, having all between-hemispheres trials require horizontal shifts of attention and all within-hemisphere trials require shifts of vertical attention might have biased the results toward our hypothesis because easier shifts of attention might result in easier T2 identification. Requiring shifts of attention across a wider distance, in contrast, should reduce the accuracy of T2 detection, biasing the data against our hypothesis. Recent data collected by Kristjansson and Nakayama (2002) indicate, however, that the AB may be less prolonged and less severe if targets occur in very distal locations rather than very proximal locations. In order to be sensitive to this issue, we performed separate analyses comparing diagonal trials and horizontal trials with within-hemisphere trials for each experiment in which dividing target items between the hemispheres reduces the AB. We report the results of these analyses in the Appendix.

*Software and equipment.* This experiment was implemented using PsyScope 1.2.2 software (Cohen, MacWhinney, Flatt, & Provost, 1993). Stimulus presentation and data collection were controlled by a Power Macintosh 7100/66.

## Results

*T1 accuracy.* We calculated the accuracy of T1 identification for 22 participants (see Figure 2A). Two participants' data were excluded from further analysis because of extremely low accuracy ( $>2.5$  SDs below the mean). We then performed an analysis of variance (ANOVA) using three variables, T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). This yielded a main effect of T1 hemisphere ( $MS$  effect = .72;  $MSE$  = .09),  $F(1, 21) = 7.80$ ,  $p < .02$ . T1 was more likely to be detected if it was directed to the right hemisphere (80%) than if it was directed to the left hemisphere (72%). A main effect of lag ( $MS$  effect = .04;  $MSE$  = .01),  $F(5, 105) = 4.32$ ,  $p < .001$ , also occurred. Pairwise comparisons ( $p < .05$ ) revealed that T1 accuracy if T2 occurred at Lag 1 (72%) was significantly less than T1 accuracy if T2 occurred at Lag 2 (75%,  $p < .03$ ), Lag 3 (77%,  $p < .02$ ), Lag 4 (79%,  $p < .001$ ), Lag 5 (77%,  $p < .01$ ), or Lag 6 (76%,  $p < .03$ ). No other main effects or interactions were significant.

*T2 accuracy given correct T1 identification.* We then calculated the accuracy of T2 identification given correct identification of T1 (Chun & Potter, 1995). Average T2 accuracy given correct T1 identification was 53% (see Figure 2B). We performed an

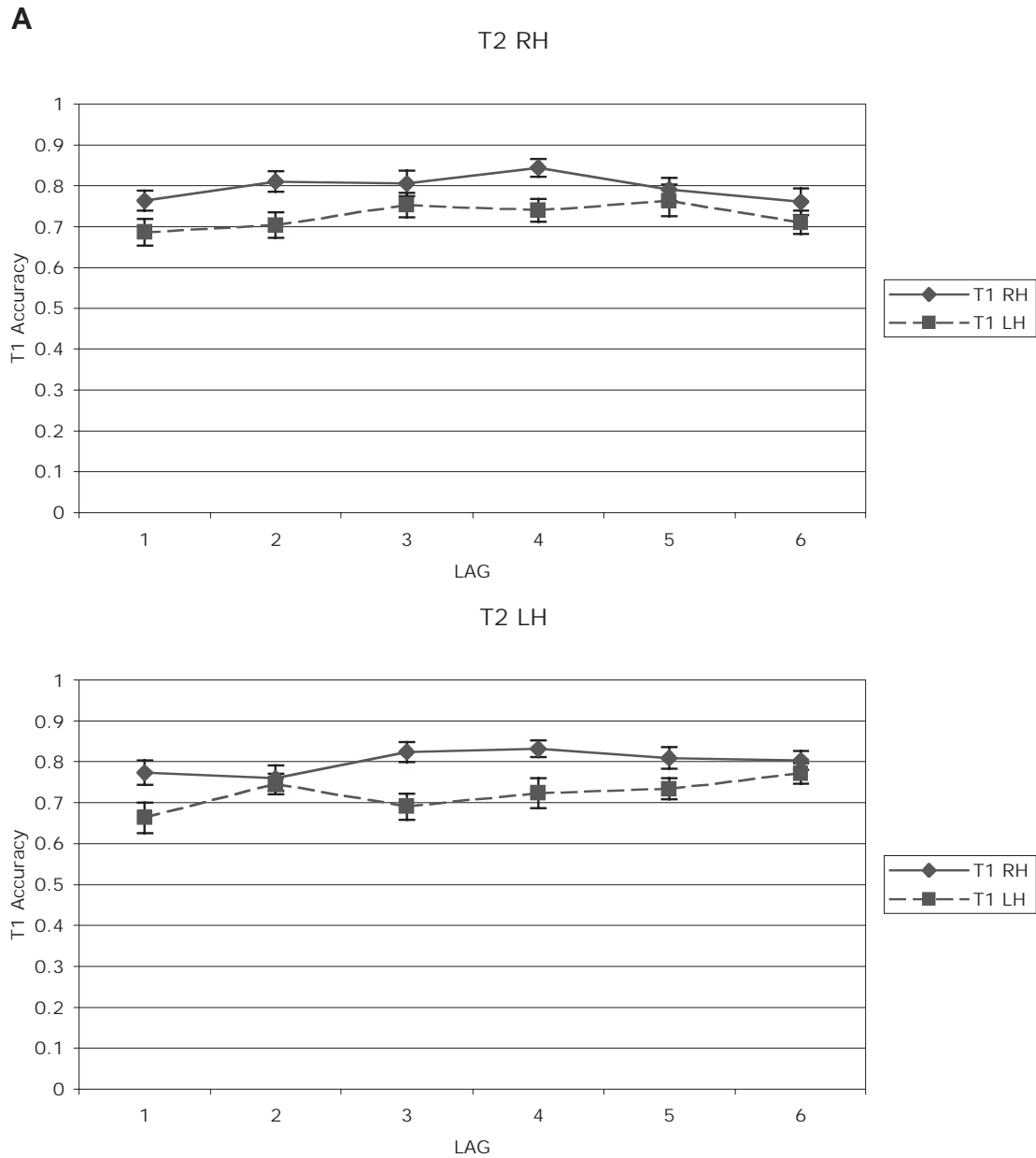
ANOVA using three variables, T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We also obtained a main effects of lag ( $MS$  effect = 1.1;  $MSE$  = .02),  $F(5, 105) = 45.65$ ,  $p < .0001$ , and T2 hemisphere ( $MS$  effect = 1.8;  $MSE$  = .072),  $F(1, 21) = 29.98$ ,  $p < .0001$ , as well as significant two-way interactions between T1 hemisphere and lag ( $MS$  effect = .06;  $MSE$  = .016),  $F(5, 105) = 3.71$ ,  $p < .01$ , and T1 hemisphere and T2 hemisphere ( $MS$  effect = .05;  $MSE$  = .024),  $F(1, 20) = 26.33$ ,  $p < .001$ , and a marginally significant interaction between lag and T2 hemisphere ( $MS$  effect = .05;  $MSE$  = .022),  $F(5, 105) = 2.7$ ,  $p < .06$ . Because the three-way interaction among T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .10;  $MSE$  = .019),  $F(5, 105) = 5.48$ ,  $p < .0001$ , is most relevant to our hypothesis, however, we focus our discussion on it. If dividing processing between the hemispheres can reduce the AB, we should observe better T2 accuracy if T1 is directed to the opposite rather than the same hemisphere as T2, and this effect should be most prominent when the AB is largest (i.e., early lags). Planned comparisons demonstrate that if T2 was directed to the left hemisphere, it was only marginally more accurately identified ( $p > .10$ ) than if T1 was directed to the right hemisphere instead of the left at any of the six lag positions. If T2 was directed to the right hemisphere, however, it was more likely to be identified if T1 was directed to the left hemisphere than if T1 was directed to the right hemisphere at Lag 1 (55% vs. 27%, respectively;  $p < .0001$ ) and at Lag 2 (51% vs. 41%, respectively;  $p < .03$ ). Differences at other lags were not significant.

## Discussion

Our results demonstrate that the AB can be reduced if targets are directed to opposite hemispheres rather than to a single hemisphere. We found that T2, when directed to the right hemisphere, was more likely to be identified and reported if T1 was directed to the left hemisphere rather than to the right hemisphere. Furthermore, these conditions did not benefit T1 processing, indicating that dividing target items between the hemispheres did not reduce the AB by reducing the bottleneck in T1 processing that causes it. Instead, dividing targets between the hemispheres allowed some process critical to item identification or representation to be performed in parallel, consequently expanding attentional capacity.

To our surprise, however, we found that the ability of item identification and representation processes to benefit from these independent processing resources was dependent on the order in which the two hemispheres received the target items directed to them. If the left hemisphere received T1 and the right hemisphere received T2, directing the items to opposite hemispheres benefited T2 report. If T1 was directed to the right hemisphere and T2 was directed to the left hemisphere, however, dividing target items to opposite hemispheres did not benefit T2 report. These data suggest that the independent processing resources of the cerebral hemisphere may only benefit item identification and representation processes if those resources are engaged in a specific order (i.e., the right hemisphere is engaged after the left hemisphere). We explored this issue further in subsequent experiments.

In the next experiment, we examined whether parallel processing continues to benefit the item identification and representation processes indexed by the AB when perceptual selection demands are lower. Previous research has suggested that dividing target



*Figure 2.* A: First target item (T1) accuracy in Experiment 1. When letter targets are presented among digit distractors, T1 is best identified if both targets are directed to the right hemisphere (RH). Its worst identification is at Lag 1. These effects did not interact with one another or with the hemisphere that received the second target item (T2). B: T2 accuracy given correct T1 identification in Experiment 1. When letter targets are presented among digit distractors, directing targets to opposite hemispheres benefits T2/T1 accuracy relative to directing both targets to the same hemisphere. These effects are more pronounced if T2 is directed to the right hemisphere. If T2 is directed to the left hemisphere (LH), T2/T1 accuracy never fully recovers from the attentional blink effect. Error bars represent 95% confidence intervals.

items between the hemispheres improves performance of some tasks because the hemispheres possess independent perceptual selection capacity (Alvarez & Cavanagh, 2005; Delvenne, 2005), rather than because they can perform the processes that follow perceptual selection in parallel. According to this idea, the extent to which dividing target items between the hemispheres benefits

performance is dependent on the relative contribution of perceptual selection and later processing (such as item identification, item representation, and response selection) to the overall attentional demands of the task (Alvarez & Cavanagh, 2005; Delvenne, 2005). Because perceptual selection processes are assumed to be constant across visual short-term memory tasks, motion tracking tasks, and

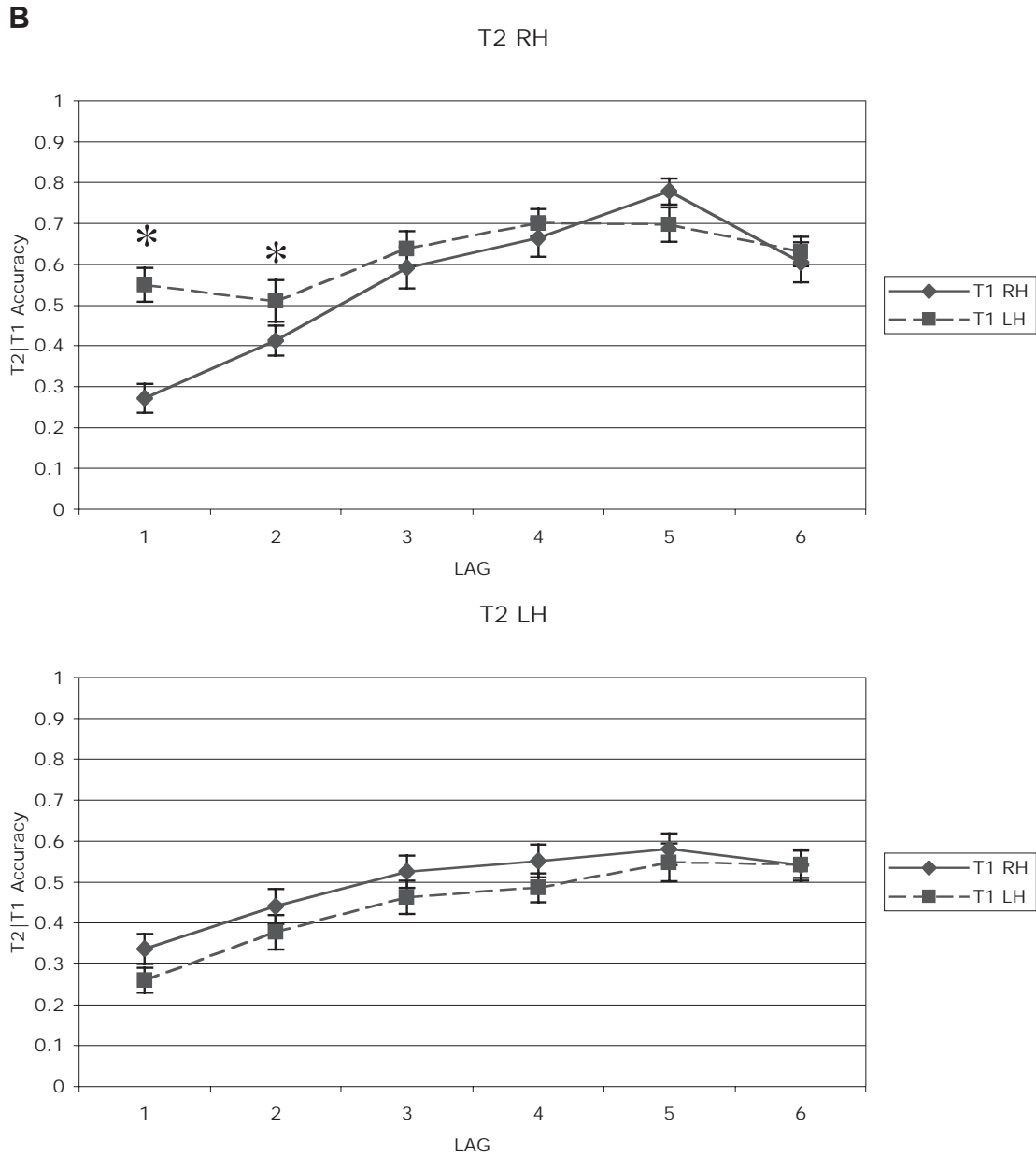


Figure 2. (continued)

visual search tasks, explanations of why dividing target items between the hemispheres improves the performance of some tasks but not others must explain why increasing the capacity of selection processes does not benefit the performance of all attentionally demanding tasks. Although one explanation for these results might be that the individual higher level processes tapped by these tasks differ in their ability to benefit from parallel processing by the cerebral hemispheres (Alvarez & Cavanagh, 2005; Delvenne, 2005), another explanation is that the relative contributions of capacity limitations at perceptual selection and capacity limitations at higher level stages differ among these tasks (Alvarez & Cavanagh, 2005; Delvenne, 2005). According to this second explanation, tasks for which perceptual selection is the most limited

processing stage will show expanded capacity when this stage is performed in parallel by the two hemispheres (Alvarez & Cavanagh, 2005; Delvenne, 2005). Tasks for which perceptual selection is not the most limited stage, however, will not benefit from increases in its efficiency, because such increases will be masked by the greater limitations of later processing (Alvarez & Cavanagh, 2005; Delvenne, 2005).

It is not clear whether dividing targets between the hemispheres benefits item identification processes or perceptual selection processes in our paradigm. Despite the fact that the AB is traditionally believed to reflect a relatively late-stage bottleneck in item identification and representation process (Chun & Potter, 1995; Joliceur, 1999; Raymond et al., 1995; Vogel et al., 1998), parallel

processing by the cerebral hemispheres may continue to improve item identification and representation by allowing perceptual selection of target items to proceed in parallel. Recent research has demonstrated that capacity limitations at relatively early processing stages may also contribute to the lag-dependent deficit in T2 processing called the AB. Inhibition of distractor items (Kristjansson & Nakayama, 2002; Loach & Mari-Beffa, 2003) or inefficient instantiation of selection criteria (Enns, Visser, Kawahara, & Di Lollo, 2001) may increase the AB effect by effectively limiting target selection. In Experiment 2, we investigated whether our observation of a reduced AB with a division of targets between the hemispheres was driven by the relatively high perceptual selection demands of our paradigm. In Experiment 1, perceptual selection of the target should have been relatively difficult because targets were not distinguished by a salient physical feature (Shih, 2000). Such conditions promote a slow, controlled selection process (Shih, 2000). When targets are distinguished by a salient physical feature, however, target selection is carried out via a rapid, automatic process (Shih, 2000; Weichselgartner & Sperling, 1987). In Experiment 2, we looked for evidence that dividing target items between the hemispheres may benefit item identification and representation processes even when perceptual selection should be relatively automatic.

### Experiment 2

In Experiment 2, we reduced demands on perceptual selection by decreasing the similarity of target and distractors. Chun and Potter (1995) reported that using American standard code for information interchange (ASCII) keyboard symbols, rather than digits, as distractors allows targets and distractors to be segregated relatively automatically because the overall forms of letters and keyboard symbols are more distinct than the overall forms of letters and digits used in Experiment 1. Increasing target salience in this manner, then, should promote target selection via a rapid, automatic process rather than a slow, controlled one (Shih, 2000). If the hemispheres benefit item identification and representation processes by bringing their independent capacity to bear on attentionally demanding selection processes, allowing selection to proceed via an automatic process should eliminate any improvement in item identification and representation that occurs when target letters are divided between the hemispheres. If we continue to find that dividing targets between the hemispheres improves T2 identification rates, however, it is more likely that the hemispheres are able to benefit item identification processes at some stage other than perceptual selection.

### Method

All methods were identical to those used in Experiment 1, unless reported otherwise below. We tested 23 right-handed, neurologically intact individuals in Experiment 2. Participants were paid \$6 per hour for their participation. We used the letters B, C, D, E, F, K, L, M, N, P, R, T, U, W, X, Y, and Z as possible targets. The characters #, &, @, and % were used as distractor items. Testing was carried out using a Macintosh G3 all-in-one computer running Psycscope 1.2.5 software.

### Results

**T1 accuracy.** We calculated the accuracy of T1 identification for 22 participants. Data from 1 participant were excluded from further analysis because of extremely low accuracy ( $>2.5$  SDs below the mean). We then performed an ANOVA using three variables, T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). No main effects or interactions were significant. Average T1 accuracy was 83% for the right hemisphere and 84% for the left hemisphere (see Figure 3A).

**T2 accuracy given correct T1 identification.** We calculated the accuracy of T2 identification given correct identification of T1 (Chun & Potter, 1995). Average T2 accuracy (given correct T1 identification) in Experiment 2 was 70%. These data were subjected to an ANOVA with three variables, T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). This yielded a main effect of lag ( $MS$  effect = .65;  $MSE$  = .021),  $F(5, 105) = 31.86$ ,  $p < .0001$  (see Figure 3B). We also found a significant two-way interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .40;  $MSE$  = .015),  $F(1, 21) = 26.04$ ,  $p < .0001$ .

Critically, we found a significant three-way interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .06;  $MSE$  = .017),  $F(5, 105) = 3.271$ ,  $p < .02$ . If targets were directed to opposite hemispheres, T2 identification was generally better than if they were directed to the same hemisphere. However, this effect varied as a function of lag; dividing inputs between the hemispheres became less advantageous to T2 identification as lag increased. Planned comparisons revealed that if T2 was directed to the right hemisphere, its identification was significantly more accurate if T1 was directed to the left hemisphere than if T1 was directed to the right hemisphere at Lag 1 (64% vs. 47%, respectively;  $p < .0001$ ). When T2 was directed to the left hemisphere, it was more accurately identified if T1 was directed to the right hemisphere than if T1 was directed to the left hemisphere at Lag 1 (61% vs. 50%, respectively;  $p < .01$ ), at Lag 2 (77% vs. 68%, respectively;  $p < .04$ ), and at Lag 4 (81% vs. 73%, respectively;  $p < .05$ ).

### Discussion

In the present experiment, we found that dividing targets between the hemispheres continued to reduce the AB when perceptual selection demands are relatively low. These data demonstrate that even conditions that should promote fast, automatic selection of targets continue to allow the independent resources of the cerebral hemispheres to improve target identification and representation processes. Other authors have speculated that the independent resources of the cerebral hemispheres can increase processing capacity only for tasks in which the bulk of attentional demand occurs during target selection (Alvarez & Cavanagh, 2005; Delvenne, 2005). Our data suggest instead that the independent processing resources of the cerebral hemispheres can increase item identification and representation capacity even if selection demands are relatively low.

We also found that reducing the similarity between targets and distractors eliminated the effect of target order on the ability of the cerebral hemispheres to use their independent processing resources to improve item identification and representation. In Experiment 1,

when targets and distractors were relatively similar, dividing targets between the hemispheres improved T2 identification accuracy only if T1 was directed to the left hemisphere and T2 was directed to the right hemisphere. In Experiment 2, when targets and distractors were less similar, directing T2 to the left hemisphere and T1 to the right hemisphere and directing T2 to the right hemisphere and T1 to the left hemisphere improved T2 identification similarly. In Experiment 3, we used a within-subjects design to replicate the impact of similarity between targets and distractors on the order in which targets must be divided between the hemispheres to benefit item identification and representation processes.

### Experiment 3

In this experiment, we contrasted the effect of using distractors that were highly and moderately similar to targets within a single group of participants. As in Experiments 1 and 2, letters served as targets. The distractors varied by block, however, such that half of the blocks contained distractors that were ASCII symbols and half contained distractors that were digits. We anticipated that we would replicate our results from Experiments 1 and 2.

#### Method

All methods used in Experiment 3 were the same as those used in previous experiments, unless noted below. We tested 24 right-handed, neurologically intact individuals in Experiment 3. Participants were paid \$8 per hour for their participation. We used the letters B, C, D, E, F, K, L, M, N, P, R, T, U, W, X, Y, and Z as possible targets. The digits 2, 3, 4, 5, 6, 7, 8, and 9 served as distractor items for high-similarity trials. The characters #, &, @, and % were used as distractor items for moderate-similarity trials. Testing was carried out using a Macintosh G3 all-in-one computer running Psyscope 1.2.5 software.

Each participant received one block of 20 high-similarity practice trials and one block of 20 moderate-similarity practice trials. Each participant performed four blocks of 192 test trials, for a total of 768 trials. Two of the blocks contained only moderate-similarity trials, whereas two of the blocks contained only high-similarity trials. Blocks of high target–distractor similarity and moderate target–distractor similarity were interleaved. The starting order of the blocks (moderate followed by high or high followed by moderate) was counterbalanced across participants.

#### Results

We calculated T1 accuracy for each individual. Data from participants whose average T1 accuracy was more than two standard deviations below the mean T1 accuracy were eliminated from subsequent analysis. Using these criteria, we analyzed data from 19 of the 24 participants.

**T1 accuracy.** We subjected T1 accuracy data to an ANOVA using the variables similarity (moderate, high), T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a significant interaction between the variables similarity and T1 hemisphere ( $MS$  effect = .28;  $MSE$  = .029),  $F(1, 18) = 9.74$ ,  $p < .01$ . Under moderate-similarity conditions, T1 was equally likely to be identified when presented to the right hemisphere (80%) as

when presented to the left hemisphere (81%; see Figure 4A). Under high-similarity conditions, however, T1 was more likely to be identified when presented to the right hemisphere (81%) than when presented to the left hemisphere (75%; see Figure 4B). These data are consistent with our results from Experiments 1 and 2. No other main effects or interactions were significant in the T1 accuracy data.

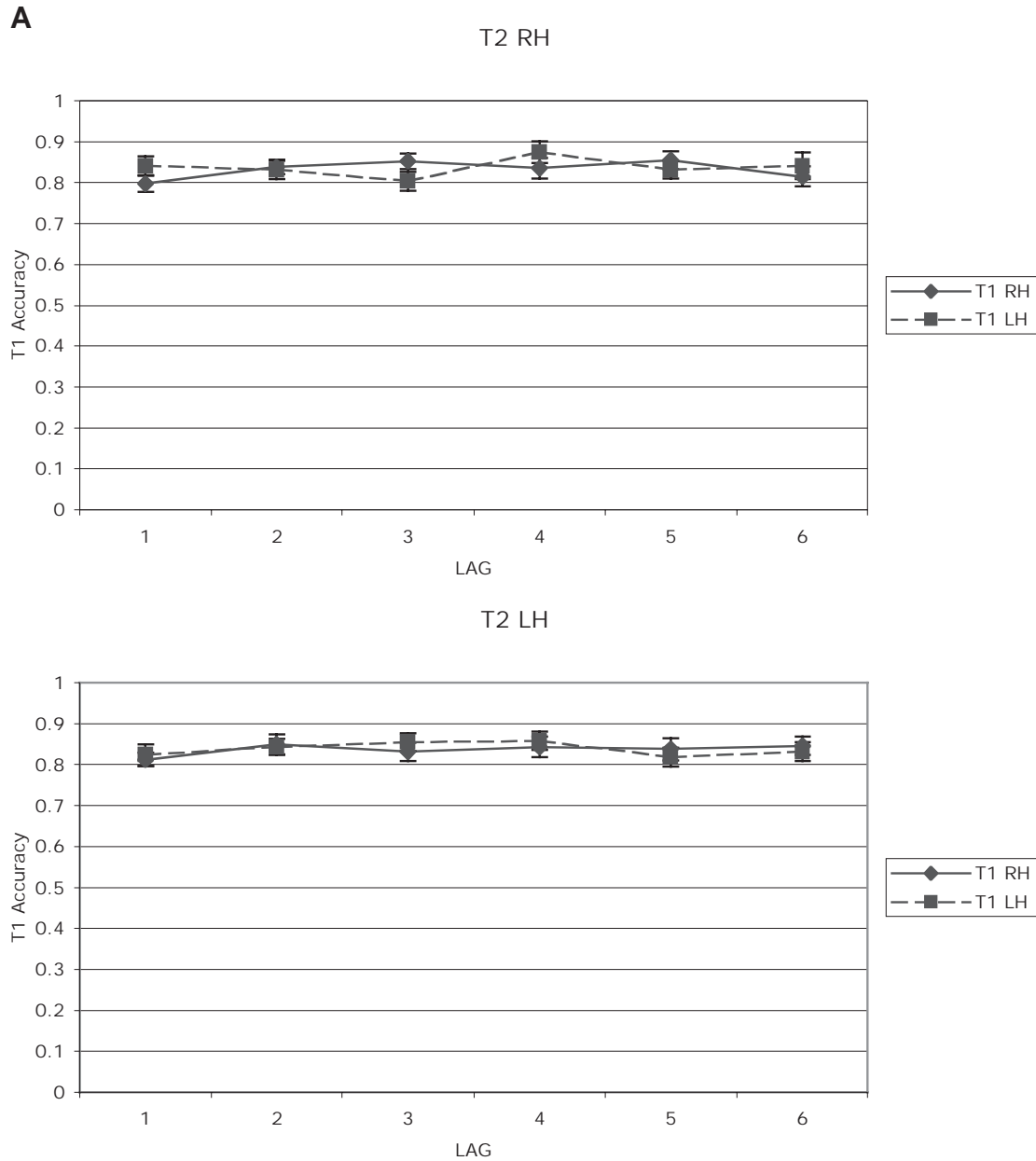
**T2 accuracy given correct T1 identification.** We calculated the accuracy of T2 identification given correct T1 identification for each condition. We subjected these data to an ANOVA using the variables similarity (moderate, high), T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of similarity ( $MS$  effect = 3.14;  $MSE$  = .186),  $F(1, 18) = 16.88$ ,  $p < .001$ . Participants were more likely to identify T2 under moderate-similarity conditions (65%) than under high-similarity conditions (53%; compare Figure 4C with Figure 4D). We found a main effect of lag ( $MS$  effect = .62;  $MSE$  = .036),  $F(4.62, 83.17) = 17.18$ ,  $p < .0001$ . The likelihood that T2 would be identified increased with increasing lag.

We found a significant interaction between the variables similarity and T2 hemisphere ( $MS$  effect = .55;  $MSE$  = .065),  $F(1, 18) = 8.5$ ,  $p < .01$ . Under moderate-similarity conditions, T2 was equally likely to be detected when it was directed to the right hemisphere (65%) as when it was directed to the left hemisphere (66%). Under high-similarity conditions, however, T2 was more likely to be detected if it was directed to the right hemisphere (58%) than if it was directed to the left hemisphere (49%).

We found a number of other significant interactions that we report but do not describe in detail in the following paragraph. Significant two-way interactions occurred between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .62;  $MSE$  = .034),  $F(1, 18) = 18.46$ ,  $p < .001$ , as well as between the variables lag and T2 hemisphere ( $MS$  effect = .05;  $MSE$  = .018),  $F(5, 90) = 2.74$ ,  $p < .03$ . Significant three-way interactions occurred among the variables similarity, T1 hemisphere, and lag ( $MS$  effect = .06;  $MSE$  = .015),  $F(3.99, 71.77) = 3.81$ ,  $p < .01$ , as well as among T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .13;  $MSE$  = .023),  $F(4.68, 84.21) = 5.41$ ,  $p < .001$ .

Of most importance, the four-way interaction among the variables similarity, T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .04;  $MSE$  = .019),  $F(5, 90) = 2.32$ ,  $p < .05$ , was significant. Planned comparisons reveal that on moderate-similarity trials, T2 identification was significantly improved if T1 was directed to the hemisphere opposite T2 at early lags (see Figure 4C). For Lags 3–6, the hemisphere to which T1 was directed did not affect T2 identification in either hemisphere. On high-similarity trials, however, the manner in which directing targets to opposite hemispheres improved T2 performance depended on the hemisphere that received T2 (see Figure 4D). If T2 was directed to the right hemisphere at Lag 1, it was more accurately identified if T1 was directed to the left hemisphere (59%) than if T1 was directed to the right hemisphere (37%,  $p < .0001$ ). If T2 was directed to the left hemisphere, however, directing T1 to the right hemisphere instead of the left hemisphere improved performance only at Lag 6 (left hemisphere = 40%, right hemisphere = 55%,  $p < .002$ ). The hemisphere to which T1 was directed did not impact T2 accuracy at any other lag point.





*Figure 3.* A: First target item (T1) accuracy in Experiment 2. When letter targets are presented among American standard code for information interchange (ASCII) symbol distractors, T1 identification does not vary with T1 hemisphere, lag, or the second target item (T2) hemisphere. B: T2 accuracy given correct T1 identification in Experiment 2. When letter targets are presented among symbol distractors, directing targets to opposite hemispheres benefits T2/T1 accuracy relative to directing both targets to the same hemisphere. These benefits are most prominent at early lags. Error bars represent the 95% confidence interval of the mean. Asterisks indicate lags at which T2 identification was significantly affected by the hemisphere that received T1. RH = right hemisphere; LH = left hemisphere.

### Discussion

Our findings from Experiment 3 generally confirm those we report for Experiments 1 and 2. Our data suggest that the relative similarity of targets and distractors determines whether the order in which items are divided between the hemispheres affects their ability to expand the capacity of item identification

and representation through parallel processing. Specifically, identification and representation of letters among digits only benefits from the independent processing capacity of the cerebral hemispheres if T1 is directed to the left hemisphere and T2 is directed to the right hemisphere. Identification and representation of letters among ASCII symbols, however, benefit from

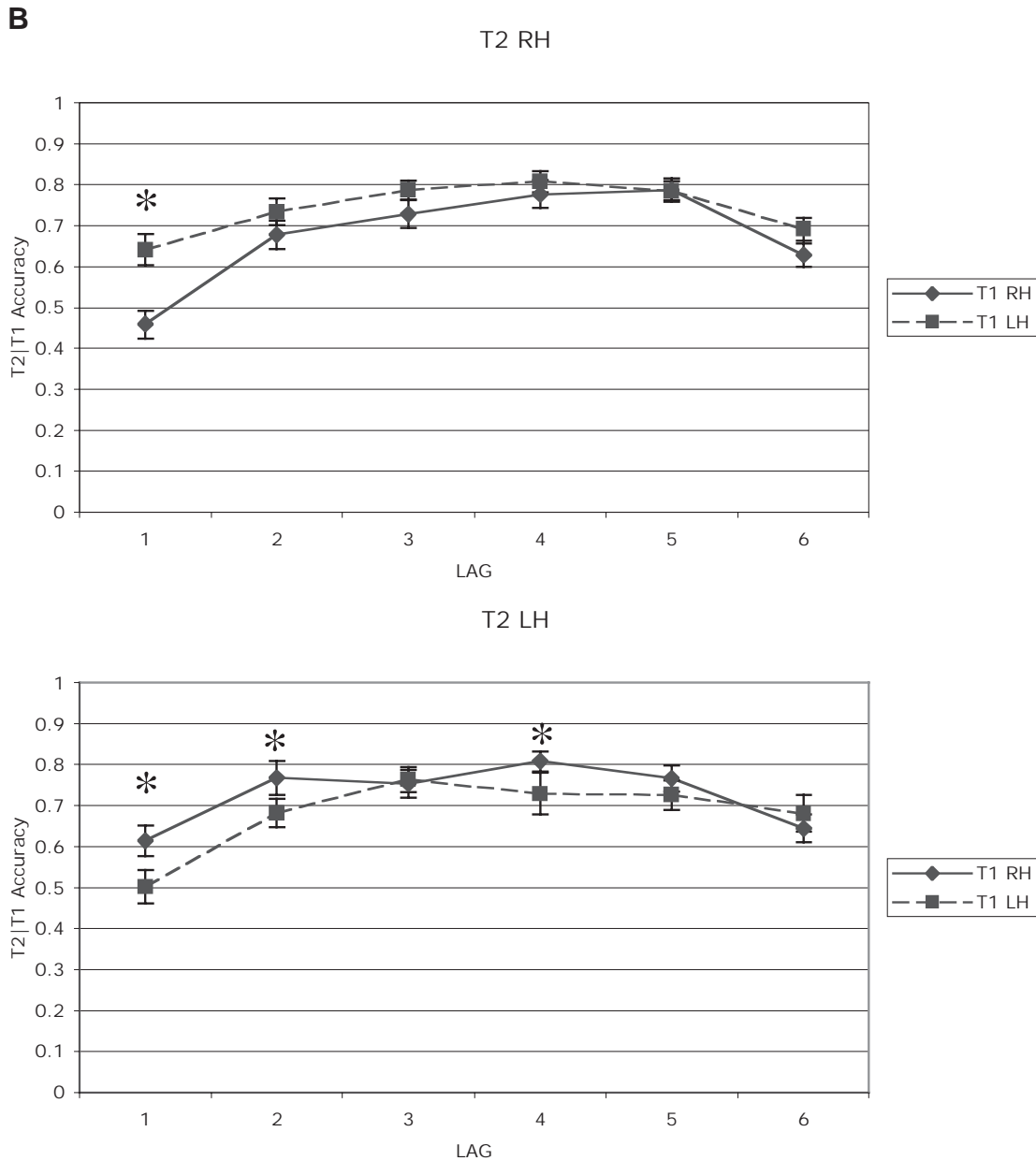
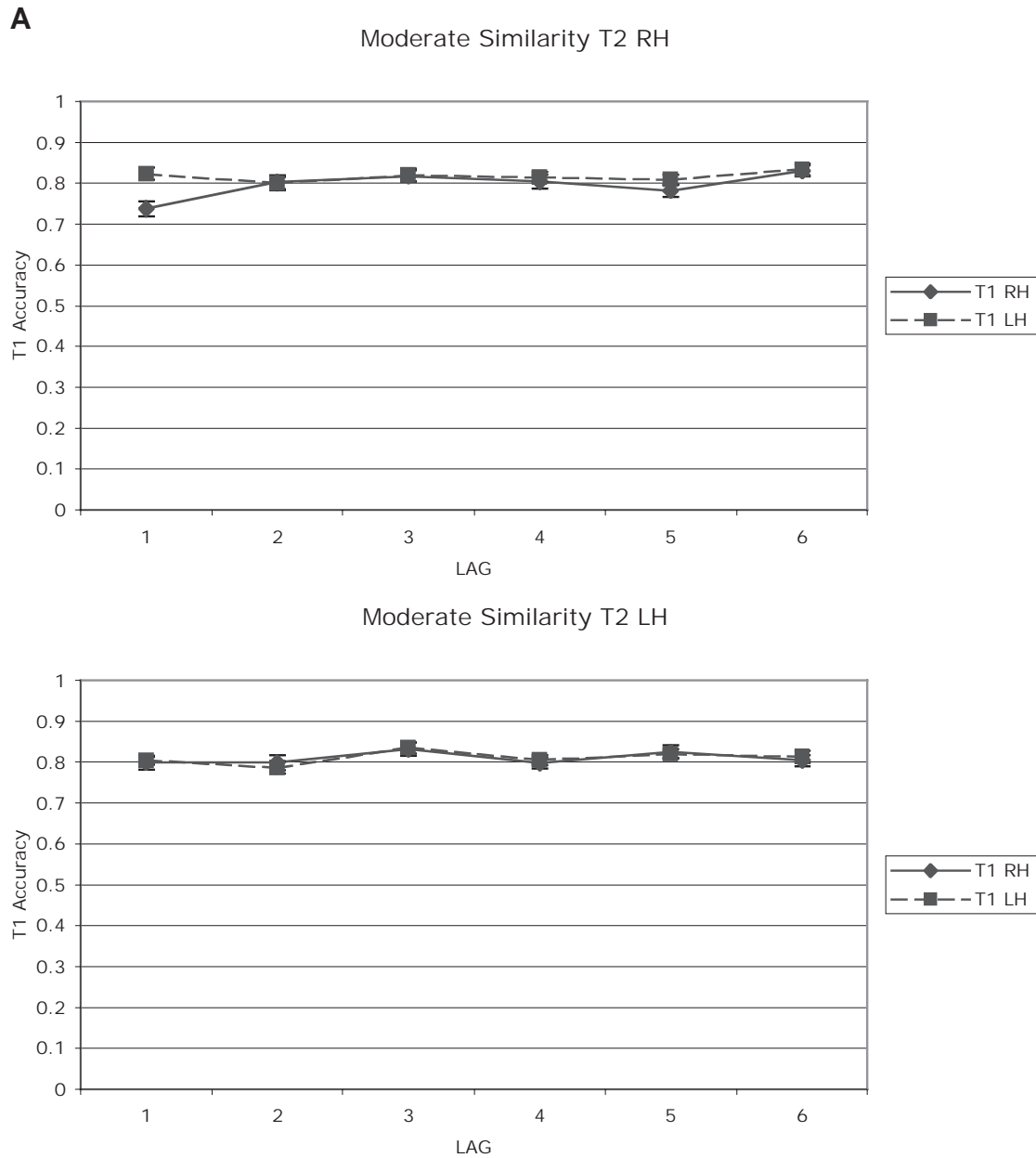


Figure 3. (continued)

the independent processing capacity of the two hemispheres regardless of the order in which the two targets are distributed between them.

The pattern of identification we observe when T2 is directed to the left hemisphere allows us to draw some conclusions regarding the nature of the effect of target order on the ability of the hemispheres to reduce the AB via parallel processing. When digits serve as distractors, as occurred in Experiment 1 and the high-similarity condition of Experiment 3, left hemisphere T2 accuracy never returns to the level of left hemisphere T1 accuracy. Instead, left hemisphere T2 accuracy remains depressed throughout the trial, regardless of whether T1 was directed to the right or left hemisphere. The relatively flat T2 performance curves we report

are similar to those observed by Giesbrecht and Di Lollo (1998), who examined T2 identification rates under conditions of integration masking. Such a flat curve indicates that T2 processing is unaffected by the completion of T1 processing; consequently, T2 processing must be impaired at a stage prior to that at which prolonged T1 processes causes the AB. Giesbrecht and Di Lollo suggested that integration masking of T2 compromises the quality of the T2 representation. Because we observed left hemisphere T2 processing decrements that are independent of the stimulus onset asynchrony (SOA) between T1 and T2 when targets and distractors are similar, we suspected that such conditions impoverish the representation of T2 items directed to the left hemisphere. This may occur either because these conditions impair the perceptual



*Figure 4.* A: First target item (T1) accuracy in Experiment 3. When letter targets are presented among American standard code for information interchange (ASCII) symbol distractors, T1 identification does not vary with T1 hemisphere, lag, or the second target item (T2) hemisphere. B: T1 accuracy in Experiment 3. When letter targets are presented among digit distractors, T1 is best identified when T1 is directed to the right hemisphere (RH). This effect does not vary with lag or the T2 hemisphere. C: T2 accuracy given correct T1 identification in Experiment 3. When letter targets are presented among ASCII symbol distractors, we observed the same effects we found in Experiment 2. Dividing targets between the hemispheres reduced the attentional blink (AB) effect, regardless of which hemisphere receives T2. D: T2 accuracy given correct T1 identification in Experiment 3. When letter targets were presented among digit distractors, we observed effects similar to those we found in Experiment 1. Dividing targets between the hemispheres reduces the AB effect relative to directing both items to the same hemisphere, if T2 is directed to the RH. If T2 is directed to the left hemisphere (LH), however, dividing targets between the hemispheres does not reduce the AB effect. Error bars represent the 95% confidence interval of the mean. Asterisks indicate lags at which T2 identification was significantly affected by the hemisphere that received T1.

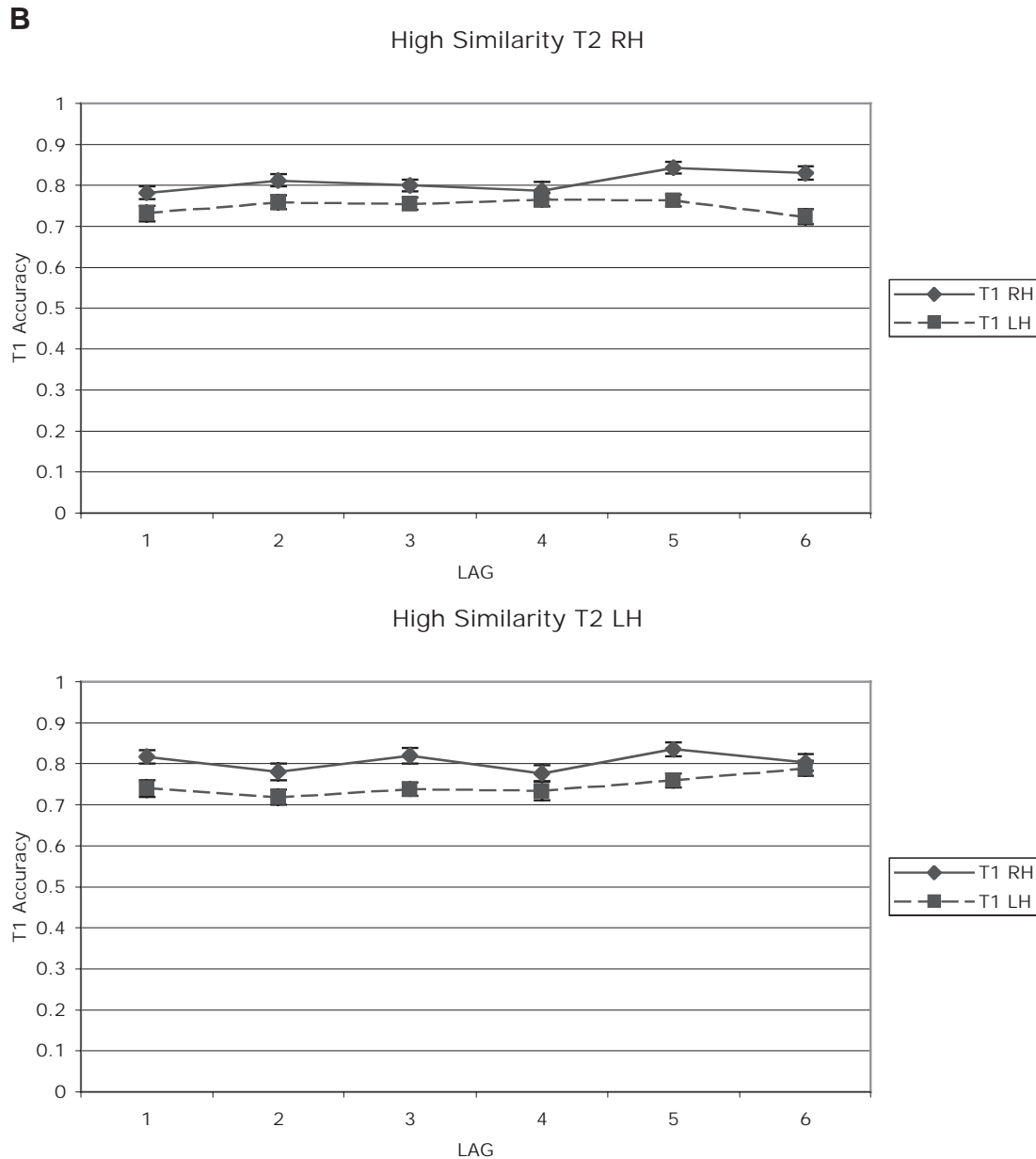


Figure 4. (continued)

selection of information directed to the right visual field when the attentional system is occupied by T1, or because they cause the representation of that information to be suppressed after selection has occurred. In either case, once processing of T1 has begun, T2 information directed to the right visual field is too poorly represented to support reliable identification.

In Experiment 3, dividing targets between the hemispheres reduced the AB effect, both when digits and ASCII symbols were used as distractor items. Despite the fact that selecting letters from ASCII symbols should place relatively low demands on selection processes, T2 identification rates under these conditions continued to improve if targets were directed to opposite hemispheres. These data suggest that the ability of the hemispheres to use their indepen-

dent processing resources to improve item identification and representation processes is not restricted to conditions in which selection demands are relatively high. Instead, our data suggest that the cerebral hemispheres can use their independent resources to improve item identification and representation processes even when selection should occur via a relatively fast, automatic process (Shih, 2000).

A possible alternative interpretation of our results is that reducing the similarity between target and distractors did not eliminate the benefits of dividing target items between the hemispheres because this manipulation reduced both attentional demands during selection and attentional demands of higher level processes; consequently, the relative demands of target selection and target identification remained constant. Previous work with the AB has

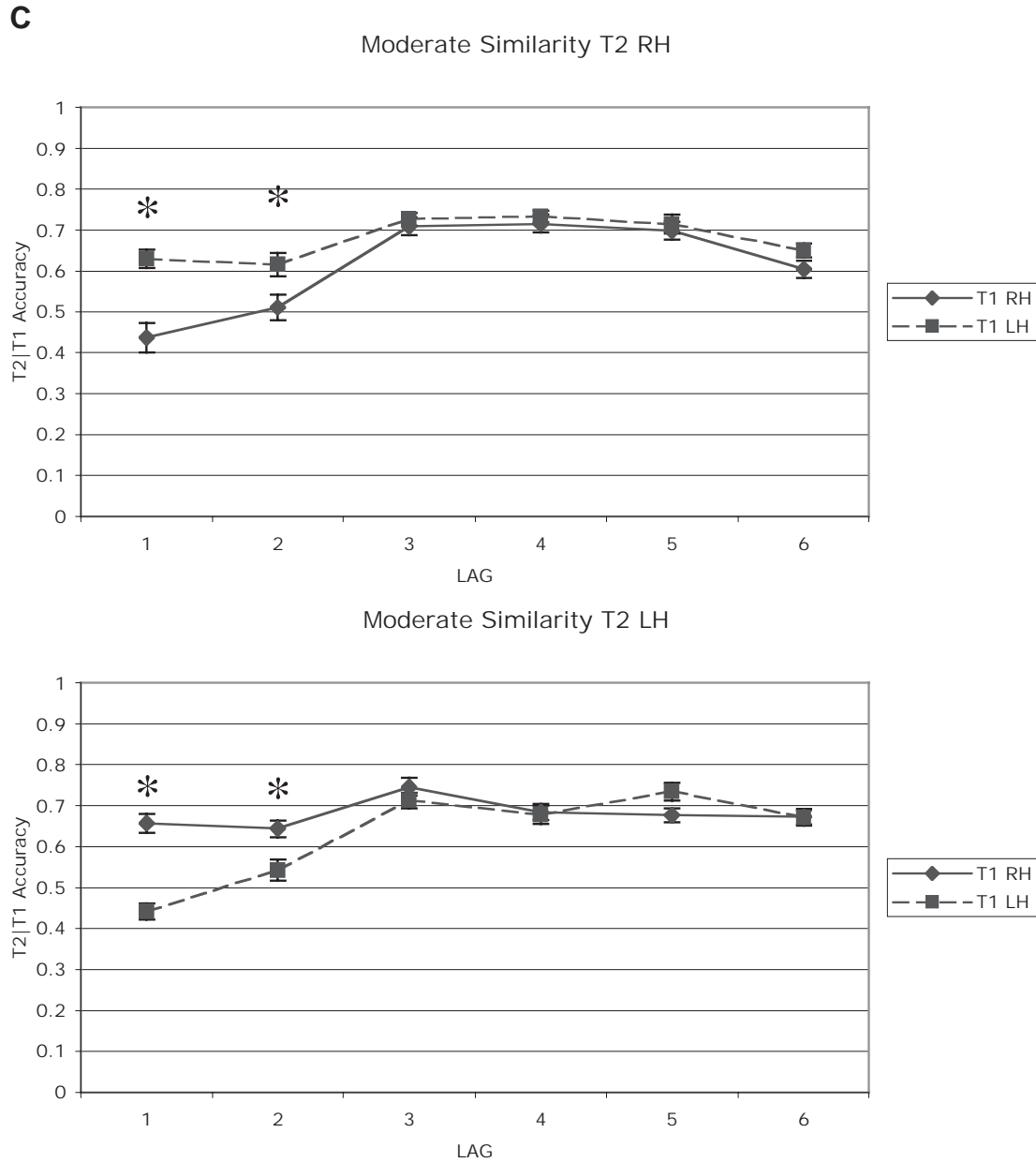


Figure 4. (continued)

shown that embedding target letters among ASCII symbols rather than digits reduces the bottleneck that causes the AB (Chun & Potter, 1995), probably because the decreased conceptual similarity between target and distractors makes item identification easier (Raymond et al., 1995). Consistent with these data, we found that using ASCII symbols rather than digits as distractors reduced the AB we observed. Our manipulation, therefore, made both selection and identification processes easier. Consequently, experimental manipulations that reduce both selection demands and higher level demands may preserve the ability of the cerebral hemispheres to improve task performance through parallel selection. We addressed this issue in Experiment 4.

#### Experiment 4

In Experiment 4, we deconfounded the relative difficulty of perceptual selection and item identification processes. In this experiment, participants identified red and green target letters interspersed among black distractors. Because color is a prepotent visual attribute, perceptual selection of the targets should occur via a fast, automatic process. Because targets and distractors are all letters and thus conceptually similar in this experiment, however, item identification and representation should be as or more attentionally demanding than when digits are used as distractors. Consequently, we should observe a large

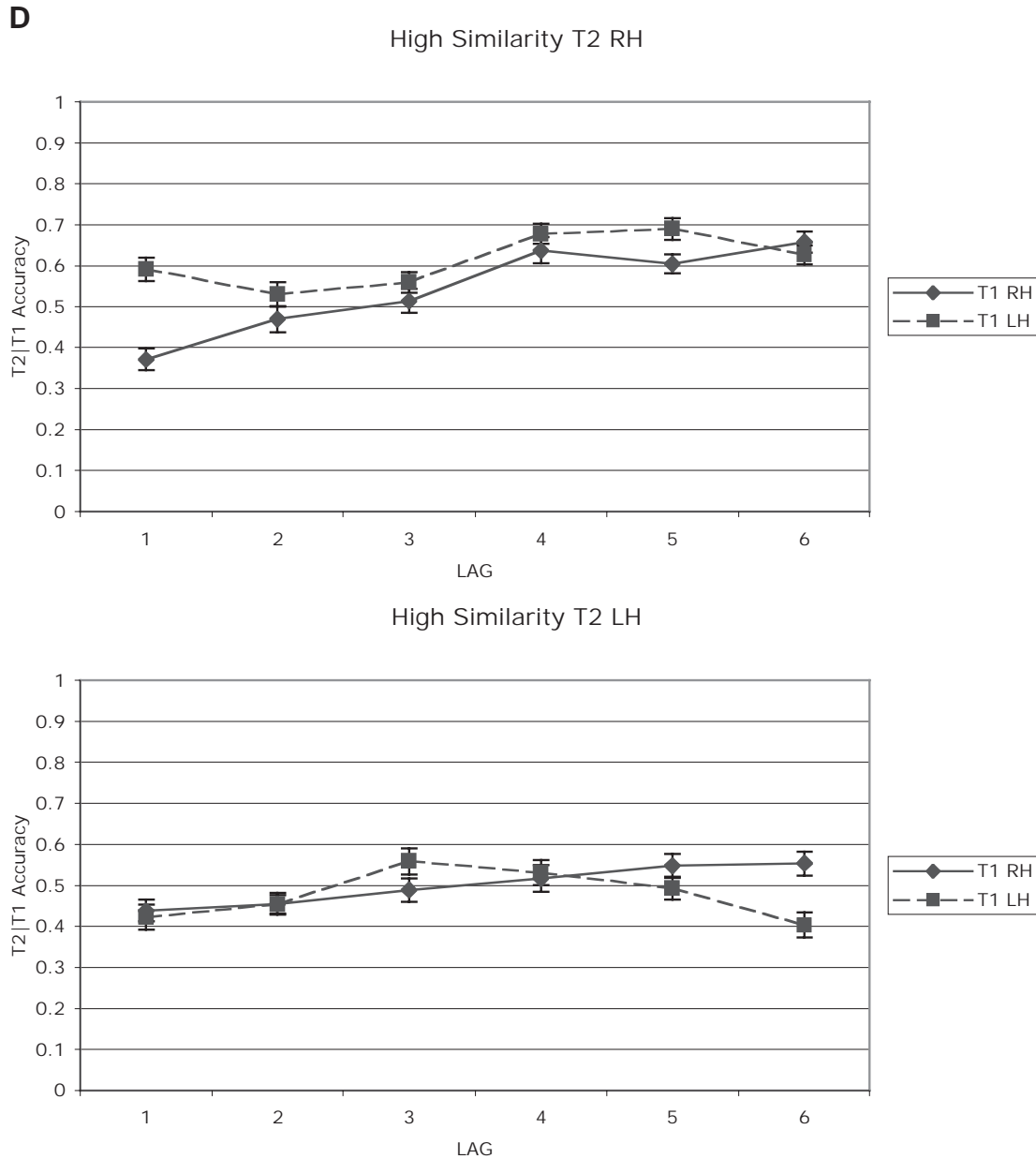


Figure 4. (continued)

AB effect. If we find that these conditions continue to allow dividing targets between the hemispheres to reduce the AB, we would conclude that this benefit is less dependent on perceptual selection processes than on item identification and representation processes.

### Method

All methods used in Experiment 4 were the same as those used in Experiments 1–3, unless noted below. We used the same four-item paradigm used in the previous experiments; in Experiment 4, however, stimuli in the RSVP sequence were presented for 60 ms and separated by a 16-ms interstimulus interval. As in the previous

experiments, a colored fixation cross was presented with each set of stimuli to help participants maintain fixation, but in this experiment, those colors were blue, yellow, magenta, and white. All other items presented in this experiment were letters. Although most letters were presented in black, one letter was presented in green and another letter was presented in red. At the end of each trial, participants were prompted to identify the green and red letters that had appeared in that sequence. In order to prevent target letters from being used as distractors in the same trial, we divided letters into two groups: (a) B, D, M, R, S, W, N, P, K, O, J, and L and (b) A, E, F, H, X, Z, C, G, V, T, U, and Y. Target items were drawn from one group, and distractor items were drawn from the

other group. The group that served as the target group and the group that served as the distractor group were counterbalanced across participants. Participants were not informed that only a subset of letters would actually serve as target items.

We tested 20 right-handed, neurologically intact individuals in Experiment 4. Participants were paid \$8 per hour for their participation. Testing was carried out using a Macintosh G3 all-in-one computer running Psyscope 1.2.5 software.

## Results

**T1 accuracy.** We calculated the accuracy of T1 identification for all participants. Data from 2 participants were excluded from subsequent analysis because of extremely low accuracy ( $>2.5$  SDs below the mean). We then performed an ANOVA on the data from the remaining 18 individuals using three variables, T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). T1 accuracy averaged 73%. No main effects or interactions were significant (see Figure 5A).

**T2 accuracy given correct T1 identification.** Next, we calculated T2 accuracy given correct T1 identification (Chun & Potter, 1995). These results were also subjected to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). This yielded a main effect of lag ( $MS$  effect = .52;  $MSE$  = .057),  $F(5, 85) = 18.85$ ,  $p < .0001$ . Planned comparisons indicate that T2 accuracy at Lag 1 (53%) and Lag 2 (55%) was significantly lower than at all other lags points ( $p < .001$ ). T2 accuracy at Lag 3 (63%) was significantly lower than that at Lag 4 (70%), Lag 5, (73%) or Lag 6 (70%;  $p < .02$ ).

We found an interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .56;  $MSE$  = .019),  $F(1, 17) = 11.01$ ,  $p < .01$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely to be identified if T1 was directed to the left hemisphere (68%) rather than to the right hemisphere (60%,  $p < .03$ ). If T2 was directed to the left hemisphere, however, it was more likely to be identified if T1 was directed to the right hemisphere (68%) rather than to the left hemisphere (61%,  $p < .05$ ).

Finally, we observed a three-way interaction among the variables T1 hemisphere, T2 hemisphere, and lag ( $MS$  effect = .03;  $MSE$  = .011),  $F(4.09, 69.54) = 2.9$ ,  $p < .03$  (see Figure 5B). Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely to be identified if T1 was directed to left rather than to the right hemisphere at Lag 1 (58% vs. 48%, respectively;  $p < .01$ ), Lag 2 (60% vs. 50%, respectively;  $p < .01$ ) and Lag 3 (68% vs. 55%, respectively;  $p < .001$ ). If T2 was directed to the left hemisphere, however, it was more likely to be identified if T1 was directed to the right rather than to the left hemisphere at Lag 1 (60% vs. 45%, respectively;  $p < .001$ ), Lag 2 (61% vs. 50%, respectively;  $p < .01$ ), and Lag 3 (68% vs. 60%, respectively;  $p < .04$ ). At early lags, then, T2 was more likely to be identified if T1 had been directed to the opposite hemisphere.

## Discussion

In Experiment 4, we found that dividing targets between the hemispheres reduced the AB. This occurred under conditions that should have promoted a fast, automatic perceptual selection process (Weichselgartner & Sperling, 1987) but still produced a large

bottleneck in item identification and representation (as indexed by the substantial AB). Despite the fact that perceptual selection should have been relatively easy but item identification and representation were relatively difficult, the two hemispheres were able to use their independent resources to reduce the AB effect. This finding suggests that the ability of the hemispheres to expand attentional capacity through parallel processing is not limited to selection processes. Even when perceptual selection demands are relatively low, the capacity of higher level processes may be functionally expanded when the hemispheres can work independently.

We also note that in Experiment 4, we observed no evidence of impaired right visual field T2 processing. Because Experiment 4 deconfounds conditions that should favor slow, controlled perceptual selection processes from those that should produce a large AB effect, it allows us to speculate regarding the conditions that produce an effect of order on the ability of the hemispheres to improve item identification processes through parallel processing. Specifically, Experiment 4, with its conceptually similar targets and distractors, produced a large AB effect, but this was not sufficient to depress left hemisphere processing of T2. Processing of T2 improved as the lag between T1 and T2 increased, regardless of whether T2 was initially processed by the right or left hemisphere. These data lead us to suspect that it is the demands of the perceptual selection process, rather than some higher level processing stage, that determine whether representations of T2 that are directed to the right visual field will be adequate to support reliable identification and representation of items.

There is one final characteristic of our paradigm that might keep perceptual selection demands relatively high, even when targets are distinguished by a salient perceptual feature: Our paradigm requires targets to be selected from different spatial locations. Some evidence suggests that requiring perceptual selection to occur at different locations places a special level of demand on perceptual selection processes to which the AB is especially sensitive (Visser, Bischof, & Di Lollo, 1999). It may be that the demands of shifting perceptual selection mechanisms between different locations are in and of themselves high enough to produce an AB effect that the hemispheres can alleviate via parallel processing. Previous work has shown that placing T1 and T2 in different locations increases the AB effect, particularly at Lag 1 (Visser, Zuvic, et al., 1999; Shih, 2000), the point at which we see the largest benefits of dividing targets between the hemispheres. This effect is believed to reflect the demands of shifting the location at which perceptual selection mechanisms operate (Visser, Bischof, & Di Lollo, 1999); any increase in the AB driven by targets occurring in different spatial locations, then, must reflect bottlenecks in the perceptual selection process rather than in the late-stage item identification process traditionally associated with the AB. Our paradigm necessarily presents items to different spatial locations. It is possible, then, that directing targets to different locations in the two visual fields eliminates any demands of shifting selection mechanisms between locations that exist when items are directed to different locations in the same visual field. If this is the case, dividing targets between the hemispheres might still reduce the AB by allowing perceptual selection to be carried out in parallel even when a salient perceptual feature identifies target items.

## Experiment 5

In Experiment 5, we investigated whether the need to shift attention between multiple locations is sufficient to cause an AB in our paradigm. We did this by further reducing the perceptual similarity of target and distractors while continuing to direct targets to different spatial locations. In Experiment 5, we used ASCII keyboard symbols that comprised very simple visual stimuli as distractor items. We expected that these targets and distractors would be easily discriminable at the perceptual selection stage (Shih, 2000; Weichselgartner & Sperling, 1987) and place relatively little demand on item identification processes because they are conceptually dissimilar (Chun & Potter, 1995; Raymond et al., 1995). Because targets will continue to be directed to different locations, however, the need for perceptual selection processes to operate at multiple locations will remain intact. Numerous studies using multistream AB paradigms have shown that shifting attention between spatial locations is specifically detrimental to T2 identification at Lag 1 (Breitmeyer, Ehrenstein, Pritchard, Hiscock, & Crisan, 1999; Visser, Bischof, & Di Lollo, 1999; Visser, Zuvic, et al., 1999). We therefore anticipated that we would observe a small AB effect that is restricted to Lag 1. We did not expect to observe an AB effect at any other lag, however. If dividing targets between the hemispheres benefits the AB by allowing perceptual selection to be carried out at different locations in parallel, we expected that any AB driven by this paradigm would be reduced when items are directed to different visual fields.

### Method

All methods used in Experiment 5 were the same as those used in Experiment 2, unless noted below. We tested 22 right-handed, neurologically intact participants who were paid \$6 per hour for their participation. The characters /, \, +, and – served as distractors.

### Results

**T1 accuracy.** We calculated T1 identification accuracy for all participants. Data from 2 participants were excluded from subsequent analysis because of extremely low accuracy ( $>2.5$  SDs below the mean). We then performed an ANOVA using three variables, T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). T1 accuracy averaged 94%. We found a significant interaction between the variables lag and T2 hemisphere ( $MS$  effect = .008;  $MSE$  = .003),  $F(5, 95) = 2.707$ ,  $p < .05$  (see Figure 6A). Newman–Keuls pairwise comparisons revealed no significant differences between any conditions within this interaction, although the greatest difference in T1 performance as a function of the hemisphere that received T2 occurred at Lags 4 and 5. Because this interaction has no bearing on our hypothesis and we have no explanation for it, it is not discussed further in this article. No other main effects or interactions were significant.

**T2 accuracy given correct T1 identification.** We then calculated the accuracy of T2 identification given correct identification of T1 (Chun & Potter, 1995). Average T2 accuracy given correct T1 identification was 89%. These data were subjected to an

ANOVA with three variables, T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = .11;  $MSE$  = .008),  $F(5, 95) = 14.45$ ,  $p < .0001$  (see Figure 6B). Planned comparisons demonstrate that T2 was significantly less likely to be identified if it immediately followed T1 in the RSVP sequence than if it occurred in any other lag position ( $p < .0001$  for all comparisons between Lag 1 and other lag positions). No other significant main effects or interactions were found.

### Discussion

In this experiment, we found that making the distractors very dissimilar to the targets greatly reduced the AB effect. We found a small AB effect only at Lag 1, when T1 and T2 occupied adjacent temporal positions. Dividing targets between the hemispheres did not affect this AB.

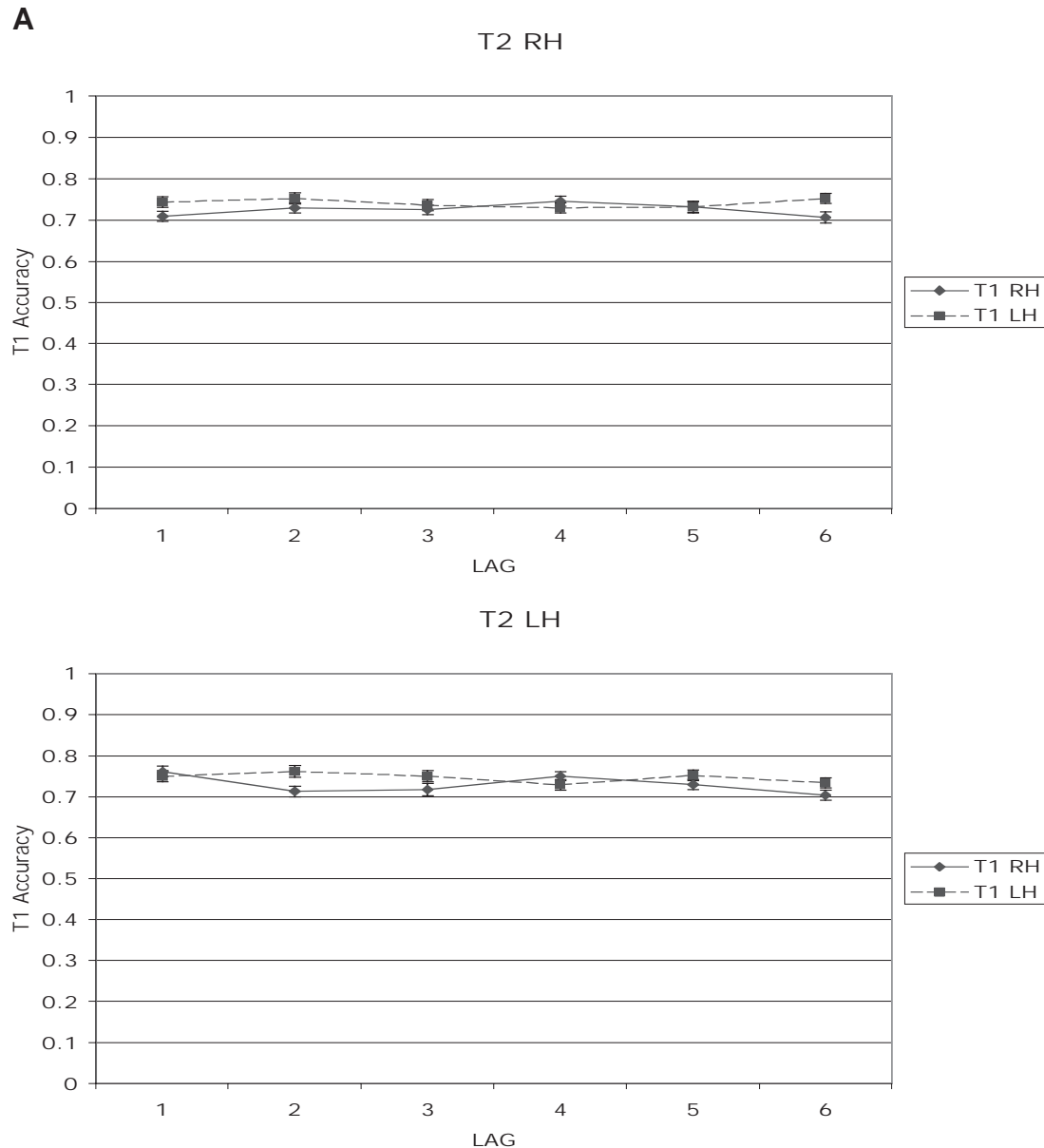
These data, then, suggest that the demands of shifting perceptual selection processes between different locations do not in and of themselves permit the cerebral hemispheres to reduce the AB through parallel processing. In Experiment 5, perceptual selection still had to be performed at multiple locations, but the perceptual and conceptual similarity between targets and distractors was very low. Demands on both selection and higher level identification and representation processes should therefore have been very low, and indeed we observed only a small depression in T2 processing when it immediately follows T1 in the RSVP stream. Although we cannot rule out the possibility that the need for perceptual selection to operate at different locations interacts with other types of selection demand to both contribute more strongly to the AB and allow the hemispheres to remediate that AB by selecting items in parallel, the results of Experiment 5 allow us to conclude that the demands of configuring selection processes to operate at different locations produce only a small AB that is not reduced when items are divided between the hemispheres.

## Experiment 6

In this experiment, we evaluated the contribution of the relative spatial locations of T1 and T2 to our finding that directing targets to different locations in different visual fields produced a smaller AB than did directing them to different locations in the same visual field. Although we interpret these data as indicating that the cerebral hemispheres reduce the AB through parallel processing, other interpretations suggest that it is the spatial arrangement of potential target locations rather than their positions in opposite visual fields that is responsible for our results.

In Experiment 6, we addressed the possibility that search biases, rather than expanded attentional capacity, produce the benefits of directing targets to opposite visual fields that we observed in our previous experiments. Our previous experiments were designed such that T2 was equally likely to be directed to either hemisphere; because T2 was prohibited from appearing in the same location as T1, however, the number of potential T2 locations in each visual field was unequal. It is possible that participants devoted more attention to the visual field that did not contain T1 because that visual field contained two potential T2 locations, whereas the visual field that received T1 contained only one potential T1





*Figure 5.* A: First target item (T1) accuracy in Experiment 4. T1 identification rates are unaffected by the hemisphere that receives T1 or by the temporal or spatial location of the second target item (T2). B: T2 accuracy given correct T1 identification in Experiment 4. When colored letter targets are presented among black letter distractors, dividing target items between the hemispheres reduces the attentional blink relative to directing both items to the same hemisphere. Error bars represent the 95% confidence interval of the mean. Asterisks indicate lags at which T2 identification was significantly affected by the hemisphere that received T1. RH = right hemisphere; LH = left hemisphere.

location. This might have led to better T2 identification when it was directed to the hemisphere opposite the one that received T1. We addressed this issue in Experiment 6 by making T2 equally likely to appear in all locations in all conditions. If we continued to find that dividing targets between the hemispheres reduces the AB, we would know that this effect is not an artifact of a bias to direct more attention to the visual field containing a larger number of potential T2 locations.

### Method

All methods used in Experiment 6 were the same as those used in Experiment 2, unless noted below. We tested 20 right-handed, neurologically intact individuals in Experiment 2. Participants were paid \$8 per hour for their participation. We used the letters B, C, D, E, F, K, L, M, N, P, R, T, U, W, X, Y, and Z as possible targets. The characters #, &, @, and % were used as distractors.

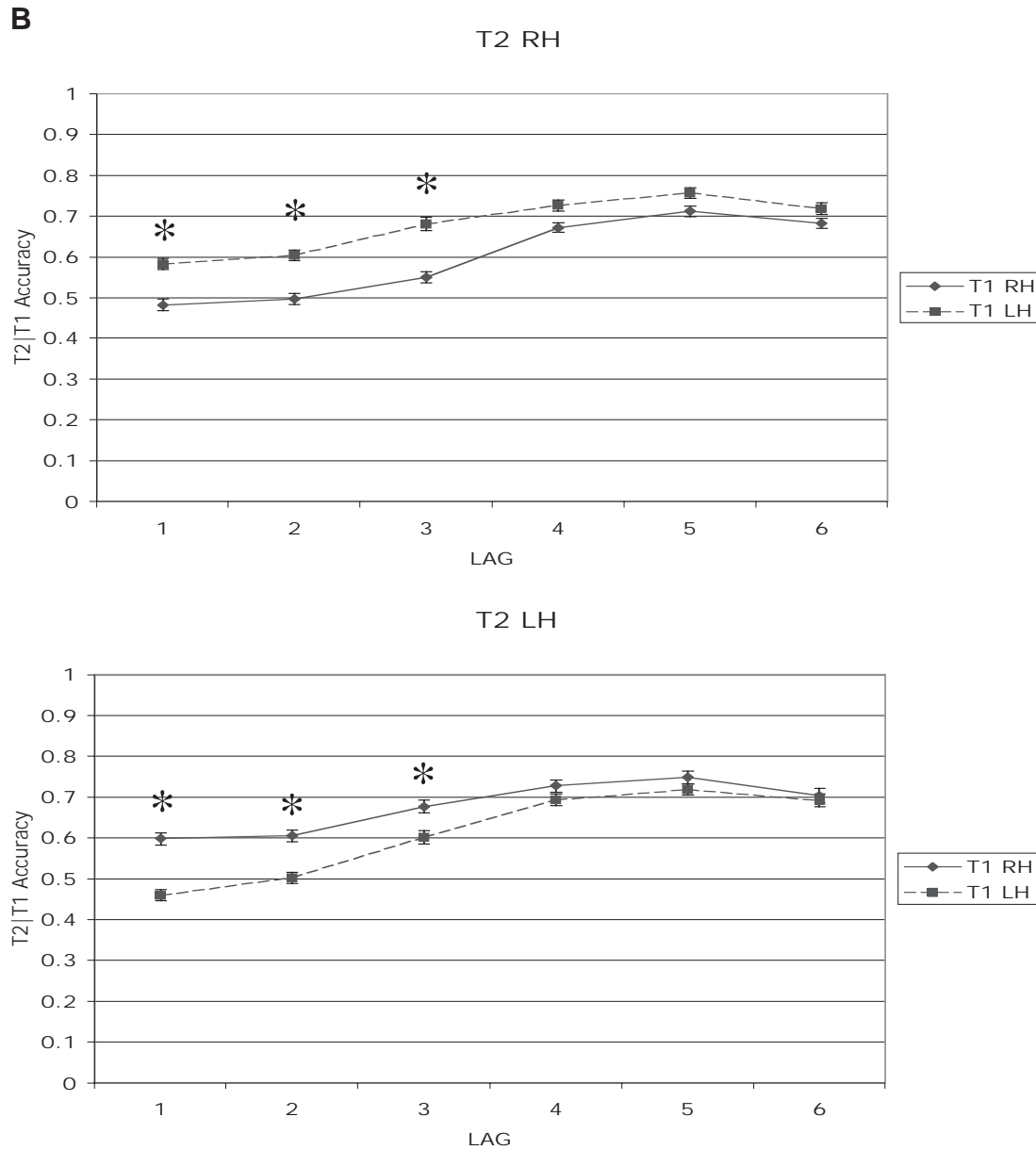


Figure 5. (continued)

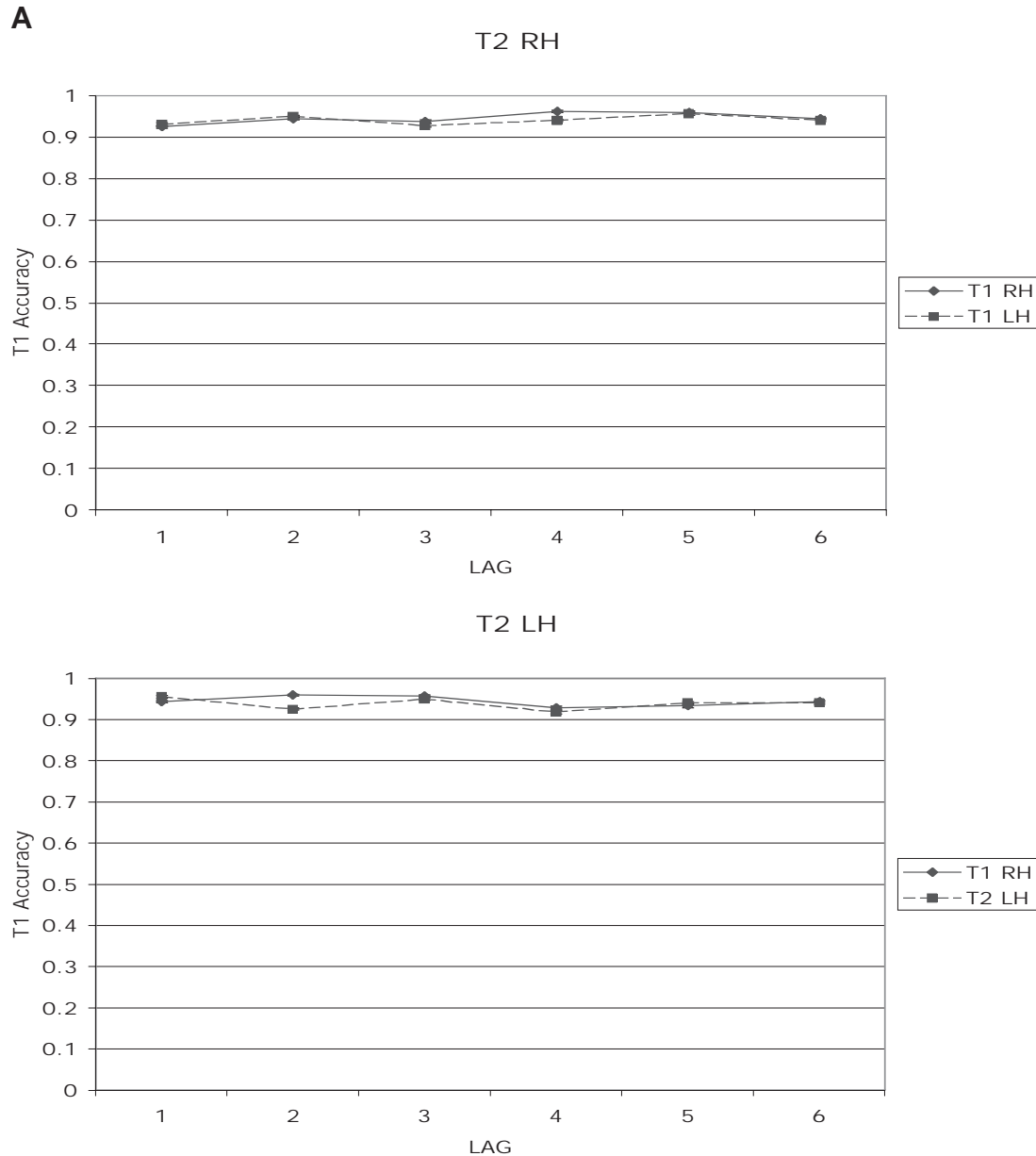
Testing was carried out using a Macintosh G3 all-in-one computer running Psyscope 1.2.5 software.

In this experiment, participants performed one block of 20 practice trials and four blocks of 192 experimental trials. In order to measure the duration of the AB, we varied the lag, or number of frames by which T2 followed T1, from one to six. T2 was equally likely to appear in any of the six lag positions. To manipulate which hemispheres received T1 and T2, we varied the spatial locations at which the two letters appeared. T1 was equally likely to occur in any of the four positions: top right visual field, bottom right visual field, top left visual field, or bottom left visual field. After T1 appeared, T2 was equally likely to appear in any of the four positions.

### Results

We calculated T1 accuracy for each participant. We rejected data from any participants whose T1 accuracy was more than two standard deviations below the mean. Using these criteria, we accepted data from 19 participants for further analysis.

In this analysis, we investigated the possibility that our previous findings were an artifact of the number of potential T2 locations in each visual field. This analysis includes all trials except those in which T1 and T2 were directed to the same location. We excluded such trials because of a recent finding that directing items to the same location in multistream variants of the AB may lead to a reverse AB effect, in which T2 is much more likely to be correctly



*Figure 6.* A: First target item (T1) accuracy in Experiment 5. When letter targets are presented among perceptually simple American standard code for information interchange (ASCII) distractors, T1 identification rates are above 90% across conditions. B: Second target item (T2) accuracy given correct T1 identification in Experiment 5. When letter targets are presented among perceptually simple ASCII symbol distractors, we observed only a small attentional blink effect at Lag 1. Directing target items to opposite hemispheres does not alleviate this effect. RH = right hemisphere; LH = left hemisphere.

detected–identified at the shortest SOA than at longer SOAs (Dell’Acqua et al., 2003; Shih, 2000). Because the T1 location was not predictive of the T2 location, any finding that dividing targets between the hemispheres reduced the AB cannot be the result of more attention being directed to the visual field that did not receive T1.

*T1 accuracy.* We subjected T1 accuracy data to an ANOVA using the variables T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). Average T1 accuracy was 86%. We

found no evidence of any main effects or interactions ( $p > .16$ ; see Figure 7A).

*T2 accuracy given correct T1 identification.* We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). We found a main effect of T2 hemisphere ( $MS$  effect = 13.6;  $MSE = .055$ ),  $F(1, 18) = 246.48$ ,  $p < .0001$ . T2 was more likely to be identified if directed to the right hemisphere (76%) than if directed to the left hemisphere (41%). We found a

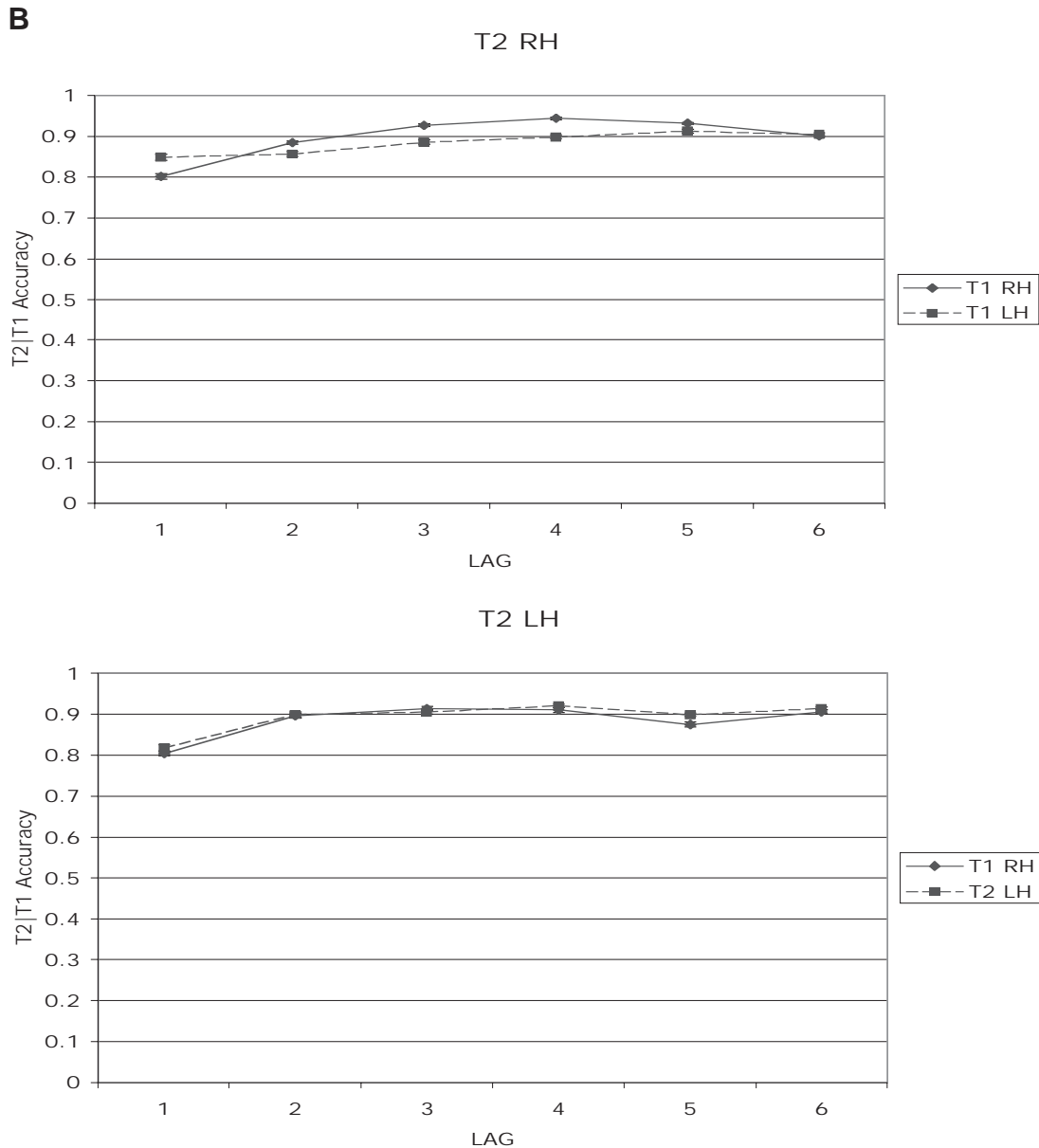
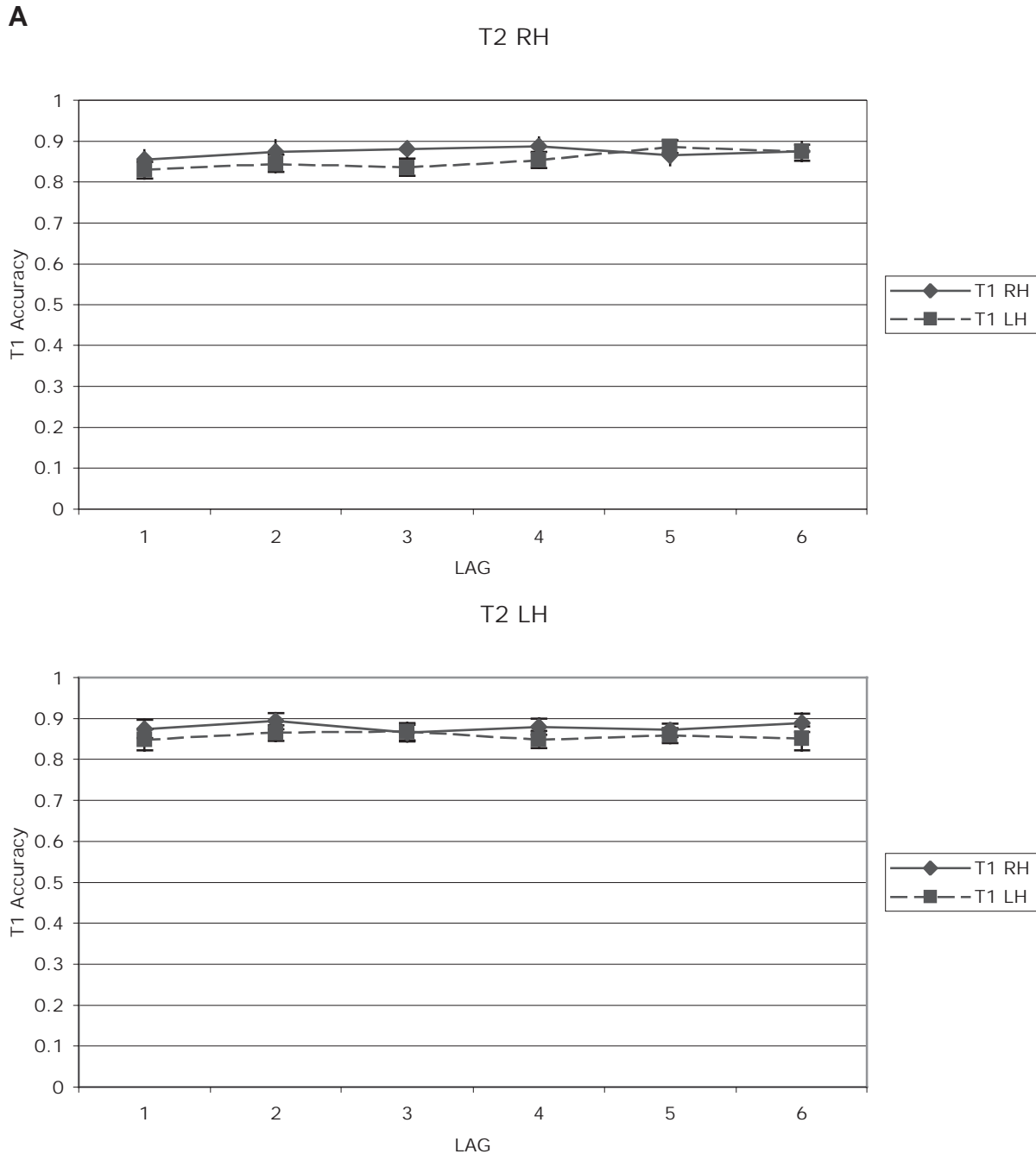


Figure 6. (continued)

main effect of lag ( $MS$  effect = .19;  $MSE$  = .008),  $F(5, 90) = 25.31$ ,  $p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (49%) than at any other lag (Lag 2 = 58%, Lag 3 = 62%, Lag 4 = 60%, Lag 5 = 61%, and Lag 6 = 61%). T2 was less likely to be identified at Lag 2 than at Lags 3, 5, and 6.

We found a significant interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .24;  $MSE$  = .009),  $F(1, 18) = 24.79$ ,  $p < .0001$ . Planned comparisons indicated that when T2 was directed to the right hemisphere, it was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere (78%) than if T1 was directed to the right hemisphere (73%). If T2 was directed to the left hemisphere, it was more likely to be

identified if T1 was directed to the right hemisphere (43%) than if T1 was directed to the left hemisphere (39%). We also found a trend toward an interaction between the variables T2 hemisphere and lag ( $MS$  effect = .02;  $MSE$  = .01),  $F(5, 90) = 2.04$ ,  $p < .09$ . Planned comparisons indicate that when T2 was directed to the right hemisphere, it was less likely ( $p < .05$ ) to be identified at Lag 1 (63%) than at any other lag (Lag 2 = 76%, Lag 3 = 80%, Lag 4 = 78%, Lag 5 = 80%, and Lag 6 = 77%). When T2 was directed to the left hemisphere, it was less likely to be identified at Lag 1 (34%) than at any other lag point (Lag 2 = 39%, Lag 3 = 45%, Lag 4 = 42%, Lag 5 = 42%, and Lag 6 = 44%). T2 was also less likely to be identified at Lag 2 than at Lags 3 and 6.



*Figure 7.* A: First target item (T1) accuracy in Experiment 6. T1 identification accuracy was equal across conditions. B: Second target item (T2) accuracy given correct T1 identification in Experiment 6. When T1 location does not predict the T2 location, dividing targets between the hemispheres reduces the attentional blink effect at Lag 1. T2 identification by the left hemisphere (LH) does not return to T1 levels. Error bars represent the 95% confidence interval of the mean. Asterisks indicate lags at which T2 identification was significantly affected by the hemisphere that received T1. RH = right hemisphere.

Finally, we found an interaction among the variables T1 hemisphere, T2 hemisphere, and lag ( $MS$  effect = .02;  $MSE$  = .007),  $F(5, 90) = 2.99$ ,  $p < .02$  (see Figure 7B). Planned comparisons indicate that T2 directed to the right hemisphere was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere

rather than to the right hemisphere at Lag 1 (71% vs. 55%, respectively) and Lag 6 (81% vs. 74%, respectively). T2 directed to the left hemisphere was more likely to be identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (37% vs. 31%, respectively) and Lag 4 (45% vs. 40%,

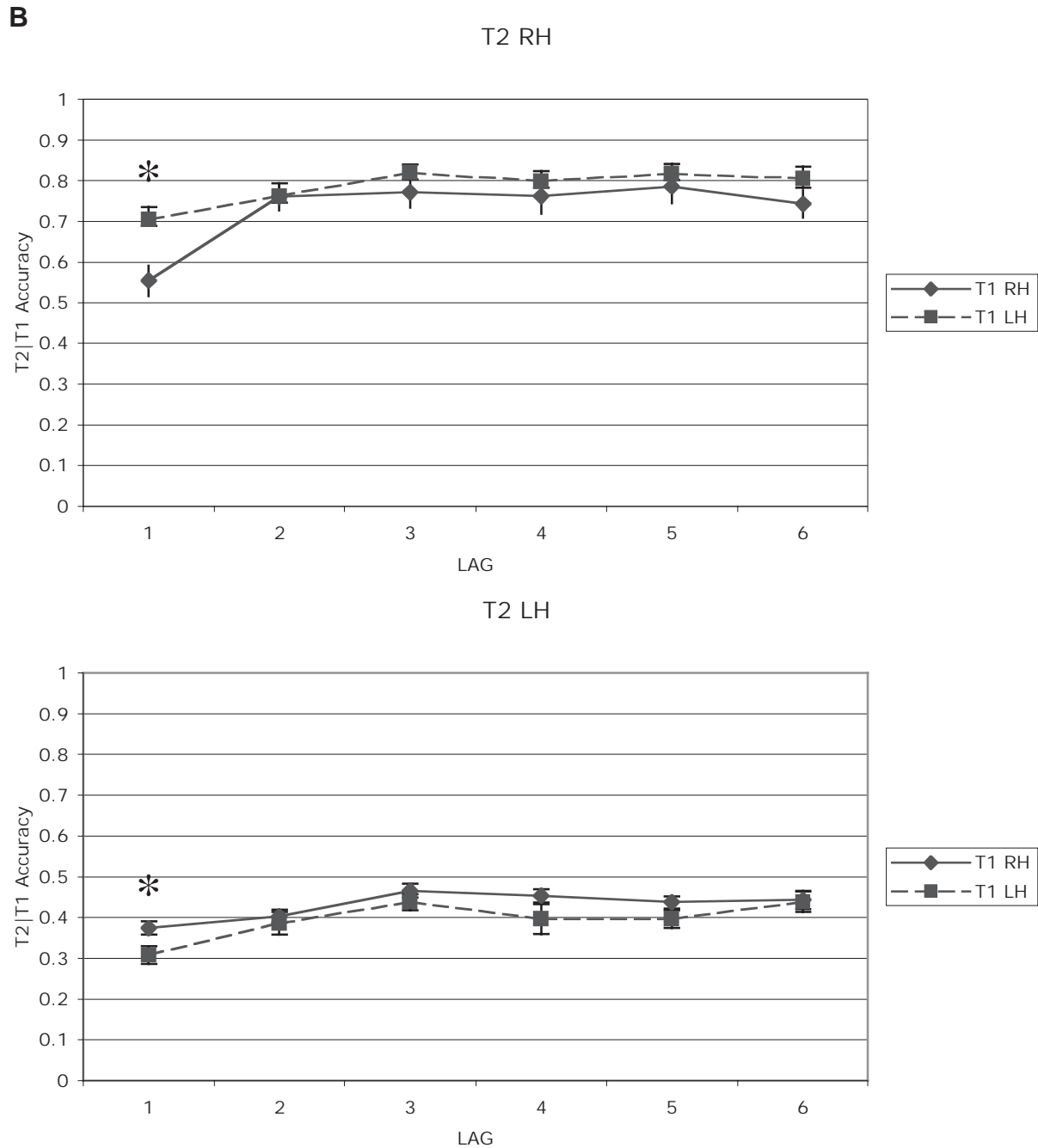


Figure 7. (continued)

respectively). No other main effects or interactions were significant.

### Discussion

The results from Experiment 6 indicate that the reductions in the AB that occurred when items were divided between the hemispheres in Experiments 1–4 were not an epiphenomenon of an asymmetry in the number of potential T2 locations in the different visual fields. In this experiment, the probability of T2

appearing at any specific location was equal in all conditions, eliminating the possibility that participants allocated more attention to the visual field that did not receive the T1 item. When we compared performance across trials in which T1 and T2 were directed to different locations, we found that directing T1 to the left hemisphere and T2 to the right hemisphere reduced the AB relative to conditions in which both targets were directed to the right hemisphere. Even if the T2 location was unpredictable, directing the two targets to opposite hemispheres reduced the AB effect.

Surprisingly, changing the likelihood that targets might appear in the same location produced a deficit in left hemisphere T2 processing. In this experiment, which used distractors that were moderately similar to targets, we found that left hemisphere T2 processing was both relatively poor and independent of its temporal relationship with T1. These results are different from those of Experiment 2 and the moderate-similarity condition of Experiment 3, in which the same combination of target and distractor items did not impair left hemisphere T2 processing. The potential of the T2 item to occur at the T1 location was the single difference between this experiment and other experiments that used ASCII symbols as distractor items, yet this difference was sufficient to introduce the impaired left hemisphere T2 processing that we observed in Experiment 1 and the high-similarity condition of Experiment 3. We hasten to remind the reader that our analysis did not include trials in which T1 and T2 were actually directed to the same location; it is therefore the potential of the T2 item to occur in the T1 location, rather than its actual occurrence, that produces the poor left hemisphere T2 processing we observed in Experiment 6.

### General Discussion

This series of experiments indicates that distributing targets between the relatively independent resources of the cerebral hemispheres improves item identification and representation capacity to reduce the AB. Previous research has demonstrated that the visual and auditory systems are sufficiently independent to functionally increase item identification and representation capacity (as measured by the AB paradigm) if task-relevant information is divided between them. Our studies indicate that the capacity of item identification and representation processes can also be expanded if information is divided between the cerebral hemispheres. We found that the effects of the processing bottlenecks that contribute to the AB can be reduced if task-relevant items are directed to opposite hemispheres. The capacity of item identification and representation processes may be more efficiently exploited if task-relevant information is directed to independent neural processors.

Our data suggest that this expansion of item identification and representation capacity occurs because the relatively independent resources of the cerebral hemispheres can operate on different items in parallel. The bottlenecks that cause the AB might be reduced by reducing in the amount of time dedicated to T1 processing at one or more stages, by directing T1 to a more powerful processor or by allowing T2 to be processed by resources unengaged by T1 processing. We can rule out the possibility that dividing targets between the hemispheres altered T1 processing. We found no evidence that directing T2 to a different hemisphere than that that received T1 improved T1 processing. In Experiment 1, we did find evidence of an effect of lag on T1 processing, such that when T2 occurred at Lag 1, T1 processing was worse than when T2 occurred at any other lag. This effect did not vary with the hemisphere that received either T1 or T2, however, indicating that it was not reduced if target items were divided between the hemispheres. We can also rule out the possibility that there is strategic variation in how the T1–T2 pair is processed depending on whether the pair was processed within or between hemispheres. Our experiments were designed to prevent the hemisphere that received T2 from affecting the resources allocated to T1. Because the hemisphere that received T1 never predicted the hemisphere

that received T2, strategic variation in the resources dedicated to T1 processing as a function of the hemisphere that received T2 was not possible. It appears, finally, that directing T2 to brain regions less involved with T1 processing reduced the AB effect. Directing task-relevant items to opposite hemispheres allows those items to avoid a processing bottleneck by accessing semi-independent processors. In other words, parallel processing by the cerebral hemispheres functionally expands the capacity of processes critical to item identification and representation to reduce the AB.

Because we found that decreases in selection demand do not reduce the benefits of dividing targets between the visual fields to the AB, parallel processing by the cerebral hemispheres is unlikely to expand item identification and representation capacity simply by expanding the capacity of selection processes. We found that dividing targets between the hemispheres reduced the AB effect across a variety of perceptual selection conditions. In Experiment 1 and the high-similarity condition of Experiment 3, dividing targets between the hemispheres reduced the AB when perceptual selection demands should have been relatively high, and in Experiment 2, the moderate-similarity condition of Experiment 3, and Experiment 4, dividing targets between the hemispheres reduced the AB when perceptual selection demands should have been relatively low. Experiment 4 provided a critical test of the idea that parallel processing can benefit item identification and representation processes even when selection demands are low. The different colors of the targets and distractors in this experiment should have made their perceptual segregation easy, but their high conceptual similarity made target identification and representation difficult. Using these conditions that should have promoted fast, automatic selection but placed large demands on item identification and representation processes, we found that dividing targets between the hemispheres continued to decrease the AB relative to directing items to a single hemisphere. Finally, Experiment 5, which used targets and distractors that were highly dissimilar both perceptually and conceptually, revealed that although the demands of perceptually selecting items from different locations may have been sufficient in our experiment to cause a small AB effect, they were not sufficient in and of themselves to allow the hemispheres to improve item identification and representation capacity via parallel processing. It is, of course, still possible that the cerebral hemispheres improve item identification capacity by performing demanding perceptual selection processes in parallel; in fact, parallelization of selection processes is essential if parallel processing is to be available to later-stage operations. The reduction in the AB that occurred when the items were divided between the hemispheres, however, did not vary with different levels of selection demand, making it likely that the ability of the hemispheres to perform postselection stages in parallel also plays a critical role in determining whether dividing target items between the hemispheres will reduce the AB.

At exactly what processing stage(s), then, does dividing target items between the hemispheres exploit the benefits of their redundant processing capacity? We can definitively state that not all processes involved in item identification can be performed in parallel by the two hemispheres, because in no experiment did dividing target items between the hemispheres eliminate the AB effect. But the AB effect is believed to index a number of distinct processes, including early visual processing (Kristjansson & Nakayama, 2002), selection (Nieuwenstein & Potter, 2006), the gen-

eration of item representations (Chun & Potter, 1995), the stabilization and maintenance of those representations (Raymond et al., 1995; Vogel & Luck, 2002), the selection and execution of responses (Jolicoeur, 1999), and the top-down configuration of target selection criteria (Enns et al., 2001; Visser, Bischof, & Di Lollo, 1999). The data from Experiment 5 allow us to confidently reject the idea that parallel processing by the cerebral hemispheres mitigates the small bottleneck that occurs when items must be selected from different spatial locations under easy selection and identification conditions. We cannot be certain which of these other potential contributors to the AB effect are amenable to parallel processing by the cerebral hemispheres, however. We appreciate that the fact that the reduction in the AB effect is strongest at early lags makes it very tempting to conclude that the benefits of parallel processing by the cerebral hemispheres must accrue at relatively early processing stages. A moment's thought, however, will remind the reader that a bottleneck in any processing stage, early or late, will be greatest when the SOA between targets is shortest. Consequently, the lag at which dividing targets between the hemispheres alleviates the AB effect is informative about the size, but not the locus, of the benefit of such a division.

Although we cannot know exactly what stage(s) in the item identification and representation process is performed in parallel by the two hemispheres, the fact that we see any benefit of dividing targets between the hemispheres at all demonstrates that that stage, or a combination of consecutive stages, must comprise the largest single bottleneck in the processing chain. To demonstrate that this must be the case, we expand on the postponement models described by Pashler and colleagues (Pashler, 1984, 1994; Pashler & Johnson, 1989; see Figure 8). In our version of the model, we suppose that there are two stages that are bottlenecked during the item identification and representation processes indexed by the AB effect. We describe two variants of these models and discuss how parallel processing of the first or second stage may affect the overall delay of T2 processing. In the first version of the model, Stage 2 is longer than Stage 1. When we compare the delay of T2 processing that occurs when all stages proceed in series with what occurs when Stage 2 is performed in parallel, we see that delay of T2 processing is reduced in the latter condition. This occurs because although Stage 1 processing of T2 cannot begin until Stage 1 processing of T1 is completed, Stage 1 processing of T2 is still completed before Stage 2 processing of T1 is completed. This allows Stage 2 processing of T2 to begin before Stage 2 processing of T1 is completed, reducing the total delay in T2 processing. If only Stage 1 can be performed in parallel, however, any decrease in delay of T2 processing by parallel Stage 1 processing results in an increase in the delay of T2 processing by Stage 2. Consequently, this arrangement does not reduce the overall delay in T2 processing. In the second version of the model, Stage 1 is longer than Stage 2. When we compare the delay of T2 processing that occurs when all stages proceed in series with what occurs when Stage 1 is performed in parallel, we see that delay of T2 processing is reduced in the latter condition. This occurs because even though T2 processing is delayed by the bottleneck in Stage 2 processing, the delay in Stage 2 processing is not as long as what would have occurred at Stage 1 had Stage 1 been performed in serial. If Stage 1 is performed in serial and Stage 2 is performed in parallel, however, there is no benefit relative to when all stages are performed in serial, because the Stage 2 processing of T1 is completed

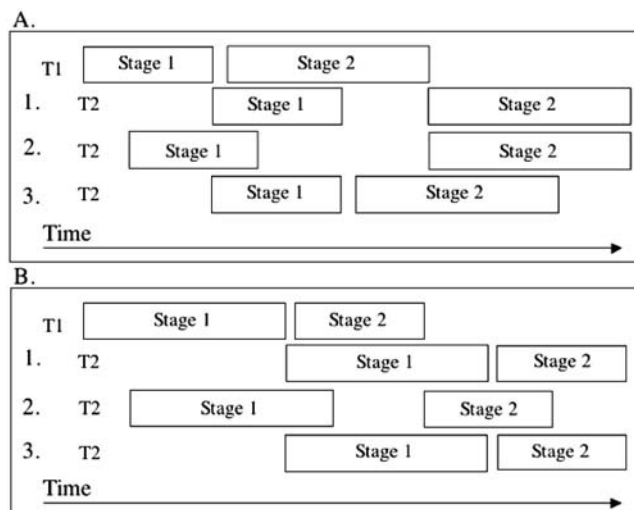


Figure 8. Stage diagrams showing the ability of parallel processing to reduce a delay in second target item (T2) processing. In both panels, Scheme 1 represents the time required to process T2 if both stages must be performed in serial, Scheme 2 represents the time required to process T2 if Stage 1 may be performed in parallel, and Scheme 3 represents the time required to process T2 if Stage 2 may be performed in parallel. A: Stage 2 is longer than Stage 1. B: Stage 1 is longer than Stage 2. In both cases, parallel processing is only helpful to performance if it is available to the longer of the two stages. Consequently, any finding that parallel processing reduces the attentional blink (AB) effect requires that parallel processing be available to the stage that has the potential to make the largest contribution to the AB effect. T1 = first target item.

before Stage 1 processing of T2. In both models, parallel processing can only reduce the delay of T2 processing if it is available to the longest processing stage. Of course, the AB effect may index many more than two processing stages; even with three or more stages, however, parallel processing can only reduce the overall processing delay if the chain of consecutive processes to which it is available is longer than that to which it is not. Consequently, whatever process may be performed in parallel by the two hemispheres must comprise a significant portion of the bottleneck that causes the AB effect, at whatever processing stage this may occur.

Our data are informative with regard to the debate over the mechanisms by which dividing task-relevant items between the hemispheres benefits performance in other divided visual field tasks. As we point out in the introduction, a number of studies demonstrate that requiring the hemispheres to communicate during item-matching tasks is beneficial to performance if demands on attentional capacity are high but is less beneficial if demands on attentional capacity are low (e.g., Banich, 1998; Banich & Belger, 1990; Belger & Banich, 1992; Passarotti et al., 2002; Weissman & Banich, 1999). It has long been supposed that dividing matching targets between the hemispheres benefits performance because it permits them to be identified in parallel (see Banich, 1998, for a fuller discussion of this issue). The null results of studies that had attempted to show parallel item identification in the connected hemispheres (Luck et al., 1989), however, led to speculation that it was the matching procedure that benefited when physically dissimilar yet matching stimuli were divided between the visual fields because the physical separation of the hemispheres prevents their



dissimilar task-irrelevant contents from interfering with the decision made about task-relevant information (e.g., Liederman, 1986). Certainly our data have not negated the possibility that “hemispheric shielding” allows information about task-relevant information to be shared between the hemispheres while isolating task-irrelevant information within the hemisphere that initially received it. They have, however, substantially strengthened the argument that dividing information between the hemispheres increases the capacity of visual attention by allowing different items to be processed in parallel by showing that such parallel processing is actually possible.

Why, then, have other studies found that item identification processes, as indexed by visual search (Luck et al., 1989) and memory for item color (Delvenne, 2005), do not benefit from parallel processing by the cerebral hemispheres? Our data suggest that it is actually because impaired left hemisphere selection may obscure the ability of the hemispheres to perform these tasks in parallel. We found that certain conditions compromise the representation of T2s directed to the left hemisphere. Specifically, when the T1 item had the potential to be difficult to segregate from the item that immediately replaced it, information directed to the left hemisphere was poorly represented. Evidence for this conclusion comes from our findings that such conditions produced relatively low, flat identification curves for T2s directed to the left hemisphere in Experiment 1, the high-similarity condition of Experiment 3, and Experiment 6. Because left hemisphere T2 identification does not return to left hemisphere T1 identification levels under these conditions, even at lags at which T1 processing is almost certainly completed, we can reasonably conclude that either poor selection or poor percept maintenance has compromised T2 representation (Giesbrecht & Di Lollo, 1998). Experiment 2, the moderate-similarity condition of Experiment 3, and Experiment 4, however, produced normal left hemisphere recovery from the AB effect. The results of Experiment 4, which used highly segregable targets and distractors but produced a robust AB effect, are especially important in allowing us to conclude that it is the potential difficulty of distinguishing T1 from distractor items, rather than the difficulty of identifying and representing T1, that determines whether the left hemisphere will be able to process T2. To our knowledge, previous investigations of the hemispheres’ ability to contribute to item identification and representation through parallel processing have not taken into account the idea that under certain conditions, the processing of one task-relevant item may prohibit the left hemisphere from selecting or representing additional items. Because our paradigm presents task-relevant items at a slight temporal offset, we could manipulate the order in which the hemispheres were engaged in target processing. This allowed us to engage the left hemisphere in processing of the initial task-relevant item, which usually yielded item identification rates equal to those of the right hemisphere. We could then compare the effect of this condition with that of directing the initial target item to the right hemisphere on right hemisphere T2 identification rates. These data showed that when the left hemisphere, rather than the right hemisphere, was engaged in processing the initial target item, right hemisphere identification rates of the T2 improved. Evidence that the hemispheres improve item identification or representation through parallel processing, then, was apparent when stimulus presentation conditions did not prevent the left hemisphere from selecting or representing the target item directed to it. Previous

studies, in which stimuli were presented simultaneously (Delvenne, 2005; Luck et al., 1989), may have failed to show such evidence because they were unable to engage both hemispheres in target processing before selection or representation of items directed to the left hemisphere was impaired by the processing of other items.

We are not the first to report condition-dependent changes in the priority given to representations of items directed to the right and left hemispheres. Fecteau, Enns, & Kingstone (2000) have demonstrated that the emergence of visual search asymmetries is dependent both on the nature of the task and on the distribution of items throughout the visual field. Although detection tasks elicit a right hemisphere advantage for search performance, localization tasks elicit a left hemisphere advantage (Fecteau et al., 2000). This indicates that the nature of operations to be performed on task-relevant material determines the hemisphere whose material will be favored in that processing. Furthermore, these advantages do not emerge unless search items are distributed throughout the visual field, indicating that their source is a bias toward material processed in the preferred hemisphere rather than an asymmetry in the representations maintained by the two hemispheres.

Data from neuropsychological patients also support the idea that biasing processes may reflect inhibition of material from the nonfavored hemisphere while the attentional system is occupied. The visual field asymmetries in the AB shown by 1 patient with unilateral extinction following right hemisphere damage (di Pellegrino, Basso, & Frassinetti, 1998) are a near mirror reversal of those we observed in neurologically intact individuals. When identifying items presented to the damaged right hemisphere, that patient showed good T2 identification when T1 was ignored but a prolonged AB (>1,200 ms) when T1 was also reported. When identifying items presented to the left hemisphere, the patient showed both good T2 identification when T1 was ignored and a normal AB effect (<500 ms) when it was not. di Pellegrino et al. (1998) interpreted these findings as reflecting competition for processing resources; whereas initial items presented to the contralesional side of space encounter no competition and can thus be processed normally, second items presented to the contralesional side of space are handicapped in the competition for resources and thus go unprocessed. Impaired right hemisphere function, then, prevents material processed by the right hemisphere from gaining access to attentional resources only when there is competition for such resources. Our neurologically intact participants, of course, showed exactly the opposite pattern of results; initial targets on the right side of space (received by the left hemisphere) are processed fairly well, whereas T2s on the right side of space tend to go unprocessed. We can apply the logic used by di Pellegrino et al. to our data. The left hemisphere reveals its disadvantage in the competition for resources when two conditions are met: first, the attentional system must already be occupied with task relevant information, and, second, segregating targets from distractors must be potentially difficult. We might interpret our data as reflecting a weakening of left hemisphere processing under these conditions, actually producing visual extinction of items processed by that hemisphere.

The pattern of T2 identification shown by the left hemisphere under conditions that encouraged asymmetric independence suggests that biasing against left hemisphere material may occur at relatively early processing stages. Under these conditions, left

hemisphere T2 processing never recovered from T1 processing by either hemisphere. An important question, then, is whether the asymmetric independence we observed in our neurologically intact adults reflects an active inhibition of material directed to the left hemisphere or reflects the inadequacy of resources available to admit items directed to the right visual field to the attentional system. Visser and colleagues have discussed at length the idea that attentional “filters” must be adjusted via top-down control to allow items to access the attentional system and that this process is attentional demanding (Enns et al., 2001; Visser, Bischof, & Di Lollo, 1999). Our data show that ongoing attentional processing effectively prevents items directed to the left hemisphere from accessing the attentional system. Whether excluding left hemisphere items from perceptual selection reflects an active or passive process is an important issue to models of attentional gating. One possibility is that suppression of material directed to the right visual field is a mechanism by which ongoing processing may be actively protected from potentially interfering information. An alternative possibility is that neglect of material directed to the right visual field is a symptom of attentional resources insufficient to simultaneously identify one item and configure perceptual selection processes to operate over the right visual field. In either case, our finding that ongoing attentional processing prevents demanding perceptual selection from occurring in the right visual field may provide telling clues about the organization of the attentional system.

Our data indicate that it is that stage of processing at which attentional demands are placed that determines whether the hemispheres can exploit their parallel architecture to functionally expand attentional capacity. Furthermore, our data support the logical notion that preventing items from progressing through early processing stages in parallel prevents the hemispheres from operating on them in parallel at later stages (Alvarez & Cavanagh, 2005). We found that in Experiments 1, 3, and 6, when T1 had the potential to be difficult to segregate from the item that immediately followed it, material directed to the right visual field was not admitted to the attentional system and thus could not benefit from the hemispheres’ redundant attentional capacity. We have also shown that dividing items between the hemispheres reduced, rather than eliminated, the AB. Together, these findings point strongly to the idea that “attentional processing is a chain of capacity limited operations, beginning with target selection and then proceeding to higher-level processes” (Alvarez & Cavanagh, 2005, p. 642). Our data clearly indicate that the load and conditions under which the attentional system is operating determine whether the first step in this chain, perceptual selection, may be performed in parallel by the two hemispheres. Our data also suggest that when this early stage may be performed in parallel by the two hemispheres, later stages in the item identification and representation processes may also benefit from the hemispheres’ semiredundant attentional capacity. Because dividing targets between the hemispheres did not eliminate the AB, however, we surmise that the hemispheres may be unable to perform some later-stage processes in parallel. These data suggest that the AB effect may reflect multiple bottlenecks, some of which the hemispheres may overcome through parallel processing, and others of which they may not.

It is clear from our data that exploitation of the hemispheres’ capacity to process information in parallel can have a powerful impact on visual item identification capacity. These data augment

that of other researchers, who have shown that the ability of the cerebral hemispheres to process information in parallel may also functionally expand the capacity of memory for item location (Delvenne, 2005) and the capacity to use attention to track moving items (Alvarez & Cavanagh, 2005). Together these studies show that parallel processing by the cerebral hemispheres allows more information that can be processed to conscious awareness by the visual system. The manner in which information flows through the visual system is not merely of academic interest; instead it has practical consequences for the amount and quality of the visual information of which an individual will be aware.

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## Appendix

## Results Segregated by Target Opposition (Horizontal or Diagonal) in Divided Visual Field Trials

In order to establish that results in our experiments were not driven solely by either those divided hemisphere trials in which targets were horizontally opposed or those in which targets were diagonally opposed, we include the separate comparisons of each of these trial types with within-hemisphere trials. We do not include these in the body of the article because doing so would make the article prohibitively long. All effects are in the predicted direction, although the relatively small number of trials occasionally prevents them from achieving conventional levels of significance.

## Experiment 1

*Results for Within-Field Trials and Divided-Field Trials With Horizontally Opposed Targets*

We subjected first target item (T1) accuracy to an analysis of variance (ANOVA) using the variables T1 hemisphere (right, left), lag (1–6), and second target item (T2) hemisphere (right, left). We found a main effect of T1 hemisphere ( $MS$  effect = .71;  $MSE$  = .11),  $F(1, 21) = 6.58, p < .02$ . T1 was more likely to be identified if directed to the right hemisphere (79%) than if directed to the left hemisphere (72%). We found a main effect of lag ( $MS$  effect = .04;  $MSE$  = .02),  $F(5, 105) = 2.8, p < .05$ . Planned comparisons indicate that T1 was less likely ( $p < .05$ ) to be identified if T2 occurred at Lag 1 (73%) than if it occurred at Lag 3 (77%) or Lag 4 (79%).

We found a marginally significant interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .04;  $MSE$  = .02),  $F(5, 105) = 2.12, p < .07$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely to adversely affect T1 processing in the left hemisphere than in the right hemisphere at Lag 2 (68% vs. 81%, respectively), Lag 4 (75% vs. 84%, respectively), Lag 5 (71% vs. 79%, respectively), and Lag 6 (68% vs. 78%, respectively). When T2 was directed to the left hemisphere, it was more likely to interfere with T1 processing in the left hemisphere than in the right hemisphere at Lag 1 (66% vs. 76%, respectively), Lag 3 (69% vs. 81%, respectively), and Lag 4 (72% vs. 84%, respectively).

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = .95;  $MSE$  = .03),  $F(5, 105) = 28.90, p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (35%) than at any other lag (Lag 2 = 41%, Lag 3 = 54%, Lag 4 = 56%, Lag 5 = 62%, and Lag 6 = 56%). T2 was less likely to be identified at Lag 2 than at Lag 3, Lag 4, Lag 5, or Lag 6. T2 was less likely to be detected at Lag 3 and Lag 4 than at Lag 5. We found a main effect T2 hemisphere ( $MS$  effect = 1.87;  $MSE$  = .09),  $F(1, 21) = 20.11, p < .001$ . T2 was more likely to be identified if directed to the right hemisphere (56%) than if directed to the left hemisphere (44%).

We found a significant interaction between the variables lag and T2 hemisphere ( $MS$  effect = .07;  $MSE$  = .03),  $F(5, 105) = 2.25,$

$p < .03$ . Planned comparisons indicate that when T2 was directed to the right hemisphere, it was less likely ( $p < .05$ ) to be identified at Lag 1 (40%) than at Lag 3 (59%), Lag 4 (65%), Lag 5 (71%), or Lag 6 (61%). T2 was less likely to be identified at Lag 2 (43%) than at Lags 3–6. T2 was also less likely to be identified at Lag 3 than at Lag 5. If T2 was directed to the left hemisphere, it was less likely to be identified ( $p < .05$ ) at Lag 1 (29%) than at any other lag (Lag 2 = 38%, Lag 3 = 48%, Lag 4 = 47%, Lag 5 = 52%, and Lag 6 = 52%). T2 was less likely to be identified at Lag 2 than at Lags 3–6.

We found a significant interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .17;  $MSE$  = .03),  $F(5, 105) = 5.32, p < .001$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere (53%) than if T1 was directed to the right hemisphere (27%) at Lag 1. At Lag 5, T2 was more likely to be identified if T1 was directed to the right hemisphere (78%) than if T1 was directed to the left hemisphere (63%). If T2 was directed to the left hemisphere, the hemisphere that received T1 did not affect performance at any lag.

*Results for Within-Field Trials and Divided-Field Trials With Diagonally Opposed Targets*

We subjected T1 accuracy data to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (1–6). We found a main effect of T1 hemisphere ( $MS$  effect = .69;  $MSE$  = .08),  $F(1, 21) = 8.45, p < .01$ . T1 was more likely to be identified if directed to the right hemisphere (80%) than if directed to the left hemisphere (73%). We found a main effect of lag,  $F(5, 105) = 3.76, p < .01$ . Planned comparisons indicate that T1 was less likely to be identified if T2 occurred at Lag 1 (71%) than if T2 occurred at any other lag point (Lag 2 = 76%, Lag 3 = 77%, Lag 4 = 79%, Lag 5 = 79%, and Lag 6 = 77%).

We found a marginally significant interaction between the variables T1 hemisphere and lag ( $MS$  effect = .04;  $MSE$  = .02),  $F(5, 105) = 1.89, p < .11$ . Planned comparisons indicate that if directed to the right hemisphere, T1 was less likely to be identified if T2 occurred at Lag 1 (77%) than if T2 occurred at Lag 4 (84%). If T1 was directed to the left hemisphere, it was less likely to be identified if T2 occurred at Lag 1 (66%) than if T2 occurred at any other lag point (Lag 2 = 74%, Lag 3 = 71%, Lag 4 = 74%, Lag 5 = 78%, and Lag 6 = 76%). T1 was also less likely to be identified if T2 occurred at Lag 3 than if T2 occurred at Lag 5.

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = 1.33;  $MSE$  = .04),  $F(5, 105) = 36.6, p < .0001$ . Planned comparisons indicate that T2 was less likely to be identified if it occurred at Lag 1 (36%) than if it occurred at any other lag point (Lag 2 = 46%, Lag 3 = 58%, Lag 4 = 64%, Lag 5 = 69%, and Lag 6 = 61%). T2 was also less likely to be identified if it occurred

(Appendix continues)

at Lag 2 than if it occurred at Lags 3–6. T2 was less likely to be identified if it occurred at Lag 3 than if it occurred at Lag 4 or Lag 5. T2 was less likely to be identified if it occurred at Lag 6 than if it occurred at Lag 5. We found a main effect of T2 hemisphere ( $MS$  effect = 1.72;  $MSE$  = .08),  $F(1, 21) = 21.92$ ,  $p < .0002$ . T2 was more likely to be identified if directed to the right hemisphere (61%) than if directed to the left hemisphere (50%).

We found a marginally significant interaction between the variables T1 hemisphere and lag ( $MS$  effect = .05;  $MSE$  = .03),  $F(5, 105) = 1.97$ ,  $p < .09$ . T1 processing in the right hemisphere impaired T2 processing more than did T1 processing in the left hemisphere at Lag 1 (32% vs. 40%, respectively). We found a significant interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = 1.56;  $MSE$  = .06),  $F(1, 21) = 24.13$ ,  $p < .0001$ . If T2 was directed to the right hemisphere, it was better identified if T1 was directed to the left hemisphere (67%) than if T1 was directed to the right hemisphere (55%). If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere (55%) than if T1 was directed to the left hemisphere (45%).

## Experiment 2

### *Results for Within-Field Trials and Divided-Field Trials With Horizontally Opposed Targets*

We subjected T1 accuracy data to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). Average T1 identification rates were 83% in the right hemisphere and 84% in the left hemisphere.

We found a marginally significant interaction between the variables T1 hemisphere and lag ( $MS$  effect = .02;  $MSE$  = .01),  $F(5, 105) = 1.89$ ,  $p < .11$ . Planned comparisons indicate that if T1 was directed to the right hemisphere, it was less likely ( $p < .05$ ) to be identified if T2 occurred at Lag 1 (80%) than if T2 occurred at Lag 2 (85%). If T1 was directed to the left hemisphere, it was less likely to be identified if T2 occurred at Lag 2 (82%) than if it occurred at Lag 4 (88%).

We found a marginally significant interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .02;  $MSE$  = .01),  $F(5, 105) = 2.14$ ,  $p < .07$ . Planned comparisons indicate that when T2 was directed to the right hemisphere at Lag 4, it was more likely to interfere with T1 processing in the right hemisphere (84%) than with T1 processing in the left hemisphere (90%). If T2 was directed to the left hemisphere at Lag 3, it was more likely to interfere with T1 processing in the right hemisphere (77%) than with T1 processing in the left hemisphere (86%).

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = .57;  $MSE$  = .03),  $F(5, 105) = 17.38$ ,  $p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (55%) than at any other lag (Lag 2 = 70%, Lag 3 = 76%, Lag 4 = 75%, Lag 5 = 74%, and Lag 6 = 64%). T2 was less likely to be identified at Lag 2 than at Lag 3. T2 was also less likely to be identified at Lag 6 than at Lags 2–4.

We found an interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .09;  $MSE$  = .03),  $F(5, 105) = 3.08$ ,  $p < .02$ . Planned comparisons indicate that if T2 was

directed to the right hemisphere, it was more likely to be identified if T1 was directed to the left hemisphere (63%) than if T1 was directed to the right hemisphere (46%) at Lag 1. If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere (62%) than if T1 was directed to the left hemisphere (50%) at Lag 1.

### *Results for Within-Field Trials and Divided-Field Trials With Diagonally Opposed Targets*

We subjected T1 accuracy data to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). No main effects or interactions were significant ( $p > .23$ ). Average T1 identification was 84% in the right hemisphere and 84% in the left hemisphere.

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = .77;  $MSE$  = .03),  $F(5, 105) = 28.98$ ,  $p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified if it occurred at Lag 1 (56%) than at any other lag (Lag 2 = 73%, Lag 3 = 76%, Lag 4 = 81%, Lag 5 = 79%, and Lag 6 = 68%). T2 was less likely to be identified at Lag 2 than at Lags 4 or 5. T2 was less likely to be identified at Lag 3 than at Lag 4. T2 was less likely to be identified at Lag 6 than at Lags 2–5.

We found a marginally significant interaction between the variables T1 hemisphere and lag ( $MS$  effect = .05;  $MSE$  = .02),  $F(5, 105) = 1.87$ ,  $p < .11$ . Planned comparisons indicate that if T2 occurred at Lag 6, its identification was more adversely affected ( $p < .05$ ) if T1 was directed to the right hemisphere (64%) than if T1 was directed to the left hemisphere (72%). We found a significant interaction between the variables T1 hemisphere and T2 hemisphere,  $F(1, 21) = 60.03$ ,  $p < .0001$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere (78%) than if T1 was directed to the right hemisphere (68%). If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere (75%) than if T1 was directed to the left hemisphere (68%).

We found a marginally significant interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .05;  $MSE$  = .02),  $F(5, 105) = 2.09$ ,  $p < .08$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (63% vs. 46%, respectively), Lag 2 (77% vs. 68%, respectively), Lag 3 (82% vs. 73%, respectively), and Lag 6 (76% vs. 64%, respectively). If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (64% vs. 50%, respectively), Lag 2 (81% vs. 68%), and Lag 4 (89% vs. 73%, respectively).

## Experiment 3

### *Results for Within-Field Trials and Divided-Field Trials With Horizontally Opposed Targets*

We subjected T1 accuracy data to an ANOVA using the variables similarity (high, moderate), T1 hemisphere (right, left), lag

(1–6), and T2 hemisphere (right, left). We found a significant interaction between the variables similarity and T1 hemisphere ( $MS$  effect = .33;  $MSE$  = .05),  $F(1, 18) = 7.17, p < .02$ . Planned comparisons indicate that under high-load conditions, T1 was more likely ( $p < .05$ ) to be identified if directed to the right hemisphere (81%) than if directed to the left hemisphere (75%). Under moderate-similarity conditions, T1 identification rates did not differ in the right (80%) and left (82%) hemispheres.

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables similarity (high, moderate), T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of similarity ( $MS$  effect = 3.67;  $MSE$  = .19),  $F(1, 18) = 19.5, p < .001$ . T2 was more likely to be identified under conditions of moderate similarity (63%) than under conditions of high similarity (51%). We found a main effect of lag ( $MS$  effect = .55;  $MSE$  = .05),  $F(5, 90) = 10.41, p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (49%) than at any other lag (Lag 2 = 50%, Lag 3 = 60%, Lag 4 = 62%, Lag 5 = 63%, and Lag 6 = 58%). T2 was less likely to be identified at Lag 2 than at Lags 3–6.

We found a marginally significant interaction between the variables similarity and lag ( $MS$  effect = .10;  $MSE$  = .05),  $F(5, 90) = 2.14, p < .07$ . Planned comparisons indicate that under high-similarity conditions, T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (44%) than at Lag 4 (57%), Lag 5 (55%), and Lag 6 (53%). T2 was less likely to be identified at Lag 2 (46%) than at Lag 4 or Lag 5. T2 was less likely to be identified at Lag 3 than at Lag 4. Under moderate-similarity conditions, T2 was less likely to be identified at Lag 1 (53%) than at Lag 3 (71%), Lag 4 (67%), Lag 5 (70%), or Lag 6 (64%). T2 was less likely to be identified at Lag 2 (55%) than at Lags 3–6. T2 was less likely to be identified at Lag 6 than at Lag 3. We found a significant interaction between the variables similarity and T2 hemisphere ( $MS$  effect = .30;  $MSE$  = .05),  $F(1, 18) = 5.56, p < .03$ . Planned comparisons indicate that under conditions of moderate similarity, T2 identification did not differ in the left (63%) and right (63%) hemispheres. Under conditions of high similarity, T2 identification was better ( $p < .05$ ) in the right (54%) than in the left (47%) hemisphere.

We found a significant interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .17;  $MSE$  = .05),  $F(5, 90) = 4.25, p < .005$ . Planned comparisons indicate that if T2 was directed to the right hemisphere at Lag 1, it was more likely to be identified if T1 was directed to the left hemisphere (58%) than if T1 was directed to the right hemisphere (40%). If T2 was directed to the left hemisphere at Lag 1, it was more likely to be identified if T1 was directed to the right hemisphere (53%) than if T1 was directed to the left hemisphere (43%).

### *Results for Within-Field Trials and Divided-Field Trials With Diagonally Opposed Targets*

We subjected T1 accuracy data to ANOVA using the variables similarity (high, moderate), T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a significant interaction between the variables similarity and T1 hemisphere ( $MS$  effect = .21;  $MSE$  = .03),  $F(1, 18) = 7.85, p < .02$ . Planned comparisons indicate that under high-load conditions, T1 was more likely ( $p <$

.05) to be identified if directed to the right hemisphere (81%) than if directed to the left hemisphere (75%). Under moderate-similarity conditions, T1 identification rates did not differ in the right (81%) and the left (81%) hemispheres.

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables similarity (high, moderate), T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of similarity ( $MS$  effect = 2.76;  $MSE$  = .21),  $F(1, 18) = 13.05, p < .005$ . T2 was more likely to be identified under moderate-similarity conditions (67%) than under high-similarity conditions (56%). We found a marginally significant main effect of T1 hemisphere ( $MS$  effect = .15;  $MSE$  = .04),  $F(1, 18) = 3.72, p < .07$ . T2 was marginally more likely to be identified if T1 was directed to the left hemisphere (62%) than if T1 was directed to the right hemisphere (60%). We found a significant main effect of lag ( $MS$  effect = .69;  $MSE$  = .05),  $F(5, 90) = 15.2, p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified if it occurred at Lag 1 (51%) than if it occurred at Lag 3 (66%), Lag 4 (67%), Lag 5 (66%), or Lag 6 (62%). T2 was less likely to be identified at Lag 2 (55%) than at Lags 3–6. T2 was less likely to be identified at Lag 6 than at Lag 4. We found a marginally significant main effect of T2 hemisphere ( $MS$  effect = .56;  $MSE$  = .18),  $F(1, 18) = 3.11, p < .10$ . T2 was marginally less likely to be identified if it was directed to the left hemisphere (59%) than if it was directed to the right hemisphere (64%).

We found a significant interaction between the variables similarity and T2 hemisphere ( $MS$  effect = .78;  $MSE$  = .09),  $F(1, 18) = 8.8, p < .01$ . Planned comparisons indicate that under moderate-similarity conditions, T2 was equally likely to be identified if T1 was directed to the right (66%) or left (67%) hemisphere. Under high-similarity conditions, T2 was more likely to be identified if T1 was directed to the left hemisphere (58%) than if T1 was directed to the right (54%) hemisphere. We found a significant interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = 2.03;  $MSE$  = .04),  $F(1, 18) = 49.74, p < .0001$ . Planned comparisons indicate that when T2 was directed to the right hemisphere, it was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere (70%) than if T1 was directed to the right hemisphere (58%). If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere (62%) than if T1 was directed to the left hemisphere (55%). We found a marginally significant interaction between the variables lag and T2 hemisphere ( $MS$  effect = .06;  $MSE$  = .03),  $F(5, 90) = 2.12, p < .07$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was less likely ( $p < .05$ ) to be identified at Lag 1 (52%) than at Lag 3 (66%), Lag 4 (72%), Lag 5 (71%), or Lag 6 (65%). T2 was less likely to be identified at Lag 2 (56%) than at Lags 3–6. T2 was less likely to be identified at Lag 6 than at Lags 4 or 5. If T2 was directed to the left hemisphere, it was less likely to be identified at Lag 1 (50%) than at Lag 3 (65%), Lag 4 (62%), Lag 5 (62%), or Lag 6 (60%). T2 was less likely to be identified at Lag 2 (54%) than at Lags 3–6. T2 was less likely to be identified at Lag 6 than at Lag 3.

(Appendix continues)

We found a significant interaction among the variables similarity, T1 hemisphere, and lag ( $MS$  effect = .06;  $MSE = .04$ ),  $F(5, 90) = 2.787$ ,  $p < .03$ . Planned comparisons indicate that when T1 was directed to the right hemisphere under conditions of moderate similarity, T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (57%) than at Lag 3 (74%), Lag 4 (72%), Lag 5 (69%), or Lag 6 (66%). T2 was likely to be identified at Lag 2 (61%) than at Lags 3–5. T2 was less likely to be identified at Lag 6 than at Lag 3. When T1 was directed to the left hemisphere under conditions of moderate similarity, T2 was less likely to be identified at Lag 1 (54%) than at Lag 2 (62%), Lag 3 (74%), Lag 4 (74%), Lag 5 (74%), or Lag 6 (66%). T2 was less likely to be identified at Lag 2 than at Lags 3–5. T2 was less likely to be identified at Lag 6 than at Lags 3–5. When T1 was directed to the right hemisphere under conditions of high similarity, T2 was less likely to be identified at Lag 1 (40%) than at Lag 3 (55%), Lag 4 (60%), Lag 5 (60%), Lag 5 (58%), or Lag 6 (53%). T2 was less likely to be identified at Lag 2 (46%) than at Lags 3–6. T2 was less likely to be identified at Lag 6 than at Lags 4–5. When T1 was directed to the left hemisphere under conditions of high similarity, T2 was less likely to be identified at Lag 1 (53%) than at Lag 3 (60%), Lag 4 (64%), or Lag 5 (65%). T2 was less likely to be identified at Lag 2 (52%) than at Lags 3–6. T2 was less likely to be identified at Lag 6 than at Lags 4 and 5. We found a marginally significant interaction among the variables similarity, lag, and T2 hemisphere ( $MS$  effect = .05;  $MSE = .03$ ),  $F(5, 90) = 1.87$ ,  $p < .11$ . Planned comparisons indicate that when T1 was directed to the right hemisphere under conditions of moderate similarity, it was less likely ( $p < .05$ ) to be identified at Lag 1 (54%) than at Lag 3 (74%), Lag 4 (75%), Lag 5 (72%), or Lag 6 (63%). T2 was less likely to be identified at Lag 2 (60%) than at Lags 3–5. T2 was also less likely to be identified at Lags 6 than at Lags 3–5. When T2 was directed to the left hemisphere under conditions of moderate similarity, T2 was less likely to be identified at Lag 1 (58%) than at Lag 3 (74%), Lag 4 (70%), Lag 5 (71%), or Lag 6 (69%). T2 was less likely to be identified at Lag 2 (62%) than at Lags 3–5. When T2 was directed to the right hemisphere under conditions of high similarity, it was less likely to be identified at Lag 1 (50%) than at Lag 3 (57%), Lag 4 (69%), Lag 5 (71%), or Lag 6 (67%). T2 was less likely to be identified at Lag 2 (53%) than at Lags 4–6. T2 was also less likely to be identified at Lag 3 than at Lags 4–6. When T2 was directed to the left hemisphere under conditions of high similarity, it was less likely to be identified at Lag 1 (43%) than at Lag 3 (57%), Lag 4 (55%), Lag 5 (52%), or Lag 6 (51%). T2 was also less likely to be identified at Lag 2 (45%) than at Lags 3 and 4. We found a significant interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .06;  $MSE = .02$ ),  $F(5, 90) = 2.83$ ,  $p < .03$ . Planned comparisons indicate that when T2 was directed to the right hemisphere, it was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere than to the right hemisphere at Lag 1 (64% vs. 40%, respectively), Lag 2 (64% vs. 49%, respectively), Lag 3 (71% vs. 61%, respectively), Lag 4 (77% vs. 68%, respectively), and Lag 5 (76% vs. 65%, respectively). When T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (57% vs. 43%, respectively).

We found a significant interaction among the variables similarity, T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .09;

$MSE = .03$ ),  $F(5, 90) = 2.78$ ,  $p < .03$ . Planned comparisons indicate that when T2 was directed to the right hemisphere under conditions of moderate similarity, it was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere rather than to the right hemisphere at Lag 1 (64% vs. 43%, respectively) and Lag 2 (69% vs. 51%, respectively). When T2 was directed to the left hemisphere under conditions of moderate similarity, it was more likely to be identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (71% vs. 44%, respectively) and Lag 2 (70% vs. 51%, respectively). If T2 was directed to the right hemisphere under conditions of high similarity, it was more likely to be identified if T1 was directed to the left hemisphere rather than to the right hemisphere at Lag 1 (63% vs. 37%, respectively), Lag 2 (58% vs. 47%, respectively), Lag 4 (74% vs. 64%, respectively), and Lag 5 (82% vs. 60%, respectively). If T2 was directed to the left hemisphere under conditions of high similarity, it was more likely to be identified if T1 was directed to the right hemisphere rather than to the left at Lag 6 (61% vs. 40%, respectively).

#### Experiment 4

##### *Results for Within-Field Trials and Divided-Field Trials With Horizontally Opposed Targets*

We subjected T1 accuracy to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of T1 hemisphere ( $MS$  effect = .07;  $MSE = .01$ ),  $F(1, 17) = 5.64$ ,  $p < .03$ . T1 was more likely to be identified if directed to the left hemisphere (74%) than if directed to the right hemisphere (72%). No other main effects or interactions were significant.

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = .52;  $MSE = .03$ ),  $F(5, 85) = 15.45$ ,  $p < .00001$ . Planned comparisons indicate that T2 was less likely ( $p < .01$ ) to be identified at Lag 1 (53%), Lag 2 (54%), and Lag 3 (61%) than at Lag 4 (69%), Lag 5 (73%), or Lag 6 (69%). T2 was also less likely to be identified at Lags 1 and 2 than at Lag 3. We found an interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .31;  $MSE = .05$ ),  $F(1, 17) = 6.51$ ,  $p < .03$ . Planned comparisons show that T2 directed to the right hemisphere was marginally more likely ( $p < .08$ ) to be identified if T1 was directed to the left hemisphere (66%) than if T1 was directed to the right hemisphere (60%). T2 directed to the left hemisphere was marginally more likely ( $p < .11$ ) to be identified if T1 was directed to the right hemisphere (66%) than if T1 was directed to the left hemisphere (61%). We found a trend toward an interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .03;  $MSE = .02$ ),  $F(5, 18) = 1.88$ ,  $p < .11$ . Planned comparisons show that when T2 was directed to the right hemisphere, it was more likely to be identified ( $p < .05$ ) if T1 was directed to the left hemisphere rather than to the right hemisphere at Lag 1 (58% vs. 48%, respectively), Lag 2 (58% vs. 50%, respectively), and Lag 3 (65% vs. 55%, respectively). If T2 was directed to the left hemisphere, it was more likely ( $p < .05$ ) to be correctly identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (46% vs. 58%, respectively). No other main effects or interactions were significant.

### Results for Within-Field Trials and Divided-Field Trials With Diagonally Opposed Targets

We subjected T1 accuracy to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a marginally significant interaction among the variables T1 hemisphere, T2 hemisphere, and lag ( $MS$  effect = .01;  $MSE$  = .007),  $F(5, 85) = 1.93$ ,  $p < .10$ . Planned comparisons indicate that T1 directed to the right hemisphere was more likely ( $p < .01$ ) to be correctly identified if T2 was directed to the left hemisphere (79%) rather than to the right hemisphere (71%) at Lag 1. No other main effects or interactions were significant.

We subjected T2 accuracy, given correct T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), lag (1–6), and T2 hemisphere (right, left). We found a main effect of lag ( $MS$  effect = 2.2;  $MSE$  = .07),  $F(5, 85) = 18.47$ ,  $p < .0001$ . Planned comparisons indicate that T2 was less likely ( $p < .05$ ) to be identified at Lag 1 (53%), Lag 2 (55%), and Lag 3 (65%) than at Lag 4 (72%), Lag 5 (73%), and Lag 6 (70%). T2 was also less likely to be identified at Lags 1 and 2 than at Lag 3. We found an interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .16;  $MSE$  = .03),  $F(1, 17) = 10.44$ ,  $p < .005$ . Planned comparisons show that T2 directed to the right hemisphere was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere (70%) than if T1 was directed to the right hemisphere (60%). T2 directed to the left hemisphere was more likely to be identified if T1 was directed to the right hemisphere (68%) than if T1 was directed to the left hemisphere (61%). We found a marginally significant three-way interaction among the variables T1 hemisphere, lag, and T2 hemisphere ( $MS$  effect = .04;  $MSE$  = .02),  $F(5, 85) = 2.28$ ,  $p < .06$ . Planned comparisons indicate that T2 directed to the right hemisphere was more likely ( $p < .05$ ) to be identified if T1 was directed to the left hemisphere rather than to the right hemisphere at Lag 1 (57% vs. 48%, respectively), Lag 2 (60% vs. 50%, respectively), Lag 3 (71% vs. 55%, respectively), and Lag 4 (76% vs. 67%, respectively). If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere rather than to the left hemisphere at Lag 1 (61% vs. 45%, respectively), Lag 2 (61% vs. 50%, respectively), and Lag 3 (72% vs. 60%, respectively). No other main effects or interactions were significant.

## Experiment 6

### Results for Within-Field Trials and Divided-Field Trials With Horizontally Opposed Targets

We subjected T1 accuracy data to an ANOVA using the variables T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). No main effects or interactions were significant ( $p > .20$ ).

Next, we subjected T2 accuracy, given corrected T1 identification, to an ANOVA using the variables T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). We found a main effect of T2 hemisphere ( $MS$  effect = 4.1;  $MSE$  = .07),  $F(1, 18) =$

210.16,  $p < .0001$ . T2 was more likely to be identified if directed to the right hemisphere (74%) than if directed to the left hemisphere (39%). We also found a main effect of lag ( $MS$  effect = .17;  $MSE$  = .009),  $F(5, 90) = 18.38$ ,  $p < .0001$ . Planned comparisons indicate that T2 was less likely to be identified ( $p < .05$ ) at Lag 1 (48%) than at any other lag (Lag 2 = 55%, Lag 3 = 61%, Lag 4 = 58%, Lag 5 = 59%, or Lag 6 = 59%). T2 was also significantly less likely to be identified at Lag 2 than at Lag 3, Lag 5, or Lag 6 ( $p < .05$ ).

We also found a significant interaction among the variables T1 hemisphere, T2 hemisphere, and lag ( $MS$  effect = .04;  $MSE$  = 3.46),  $F(5, 90) = 3.46$ ,  $p < .01$ . Planned comparisons ( $p < .0001$ ) indicate that if T2 was directed to the right hemisphere at Lag 1, directing T1 to the left hemisphere improved T2 identification (70%) relative to directing T1 to the right hemisphere (55%). Directing targets to opposite hemispheres did not improve performance at any other lag point.

### Results for Within-Field Trials and Divided-Field Trials With Diagonally Opposed Targets

We subjected T1 accuracy data to an ANOVA using the variables T1 hemisphere (right, left), T2 hemisphere (right, left), and lag (1–6). We found a marginally significant main effect of T1 hemisphere ( $MS$  effect = .07;  $MSE$  = .02),  $F(1, 18) = 2.83$ ,  $p < .11$ . T1 was marginally more likely to be identified if directed to the right hemisphere (88%) rather than to the left hemisphere (85%). No other main effects or interactions approached significance.

We subjected T2 accuracy data, given correct T1 identification, to an ANOVA using the variables T1 hemisphere, T2 hemisphere, and lag. We found a main effect of T2 hemisphere ( $MS$  effect = 13.17;  $MSE$  = .05),  $F(1, 18) = 262.32$ ,  $p < .00001$ . T2 was more likely to be identified if directed to the right hemisphere (78%) than if directed to the left hemisphere (43%). We also found a main effect of lag ( $MS$  effect = .22;  $MSE$  = .01),  $F(5, 90) = 19.01$ ,  $p < .00001$ . Planned comparisons indicate that T2 was less likely to be identified if presented at Lag 1 (49%) than if presented at any other lag (Lag 2 = 60%, Lag 3 = 64%, Lag 4 = 62%, Lag 5 = 63%, and Lag 6 = 63%). T2 at Lag 2 was marginally less likely to be identified than T2 at Lag 3 ( $p < .08$ ).

We found an interaction between the variables T1 hemisphere and T2 hemisphere ( $MS$  effect = .75;  $MSE$  = .01),  $F(1, 18) = 76.06$ ,  $p < .0001$ . Planned comparisons indicate that if T2 was directed to the right hemisphere, it was more likely ( $p < .0001$ ) to be identified if T1 was directed to the left hemisphere (81%) than if T1 was directed to the right hemisphere (73%). If T2 was directed to the left hemisphere, it was more likely to be identified if T1 was directed to the right hemisphere (47%) than if T1 was directed to the left hemisphere (39%). No other main effects or interactions were significant.

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