Journal of Vision (2023) 23(13):3, 1–17

Testing hemifield independence for divided attention in visual object tasks

Dina V. Popovkina
Department of Psychology, University of Washington, Seattle, WA, USA

John Palmer
Department of Psychology, University of Washington, Seattle, WA, USA

Cathleen M. Moore
Department of Psychological and Brain Sciences, University of Iowa, Iowa City, IA, USA

Geoffrey M. Boynton
Department of Psychology, University of Washington, Seattle, WA, USA

In this study, we asked to what degree hemifields contribute to divided attention effects observed in tasks with object-based judgments. If object recognition processes in the two hemifields were fully independent, then placing stimuli in separate hemifields would eliminate divided attention effects; in the alternative extreme, if object recognition processes in the two hemifields were fully integrated, then placing stimuli in separate hemifields would not modulate divided attention effects. Using a dual-task paradigm, we compared performance in a semantic categorization task for relevant stimuli arranged in the same hemifield to performance for relevant stimuli arranged in separate left and right hemifields. In two experiments, there was a reliable decrease in divided attention effects when stimuli were shown in separate hemifields compared to the same hemifield. However, the effect of divided attention was not eliminated. These results reject both the independent and integrated hypotheses, and instead support a third alternative – that object recognition processes in the two hemifields are partially dependent. More specifically, the magnitude of modulation by hemifields was closer to the prediction of the integrated hypothesis, suggesting that for dual tasks with objects, dependent processing is mostly shared across the visual field.

Introduction

In the domain of vision, making judgments about two simultaneously presented stimuli can reduce performance: for example, it is harder to recognize two objects at the same time compared to one (Popovkina, Palmer, Moore, & Boynton, 2021). This effect is present for some stimuli and judgments (words, objects, faces; e.g., White, Palmer, & Boynton, 2018) but not for others (colors, line orientation; e.g. White, Runeson, Palmer, Ernst, & Boynton, 2017). When they do occur, divided attention effects reflect limitations in various stages of visual processing of multiple stimuli, such as encoding in perception, or capacity limits in attention or memory. In dual tasks, a source of these limits might be related to the processes shared between stimuli at two spatial locations. Our question is whether the possible independence between processing of the left and right visual hemifields modulates the effects of divided attention in object-based tasks (Sereno & Kosslyn, 1991; Awh & Pashler, 2000; Alvarez, Gill, & Cavanagh, 2012). Alternative hypotheses for hemifield effects are elaborated below, along with their predictions.

Alternative hypotheses

Here, we consider three possibilities for how processing in the left and right hemifields might be related. The first possibility is that the *hemifields are independent* (e.g. Alvarez et al., 2012). That is, separate processes in each hemifield allow for independent judgments of multiple objects. In this case, divided attention effects are expected when objects fall within the same hemifield, and no divided attention effects are expected when objects fall in separate hemifields.

A second possibility is that *hemifields are integrated* (e.g., Luck, Hillyard, Mangun, & Gazzaniga, 1994). That is, there is no distinction between processes in the left and right hemifields. In this case, judgments of objects should be equivalent across the visual field,

Citation: Popovkina, D. V., Palmer, J., Moore, C. M., & Boynton, G. M. (2023). Testing hemifield independence for divided attention in visual object tasks. *Journal of Vision*, *23*(13):3, 1–17, https://doi.org/10.1167/jov.23.13.3.

https://doi.org/10.1167/jov.23.13.3 Received March 31, 2023; published November 3, 2023 ISSN 1534-7362

and divided attention effects should be identical when multiple objects fall in separate hemifields and when they fall in the same hemifield.

These two alternative hypotheses present opposing predictions. A third, intermediate possibility is that *hemifields are partially dependent* (e.g., Cohen, Rhee, & Alvarez, 2016). That is, there is a distinction between processes in the left and right hemifields, but these processes are not independent. In this case, the prediction is intermediate between the predictions of the other two hypotheses: namely, a smaller divided attention effect when multiple objects fall in separate hemifields than when they fall in the same hemifield.

Previous studies

Previous work examining hemifield effects for judgments of multiple stimuli has produced mixed evidence, supporting all three hypotheses outlined above to varying degrees. The most consistent evidence in favor of the independent hemifield hypothesis comes from studies of multiple object tracking. For example, participants are able to track nearly twice as many targets when they are presented separately in left and right hemifields, relative to when they are presented in the same hemifield (Alvarez & Cavanagh, 2005). Holcombe and Chen (2012) report a similar result, showing that the speed dependence of tracking two targets in separate hemifields is similar to tracking one target.

In visual search studies, there is evidence for integrated processing. For example, Luck et al. (1994) showed that participants had similar target search rates for visual stimulus arrays presented in the same hemifield as for arrays spanning the two hemifields. However, other visual search studies have produced evidence against the integrated hemifield hypothesis. For example, Alvarez et al. (2012) report that in a visual search task (reporting the orientation of a T among rotated Ls), participants had faster response times when the relevant locations spanned across the two hemifields, relative to when the locations were in the same hemifield. They propose that this result is consistent with independent processing in the two hemifields, particularly when the task requires attentional selection of multiple relevant spatial locations. More recently, Cohen et al. (2016) reported that change detection performance was better when object stimulus arrays spanned across hemifields than when they were presented in the same hemifield. They interpret this result as consistent with the predictions of the partially dependent hemifield hypothesis. Importantly, none of these visual search studies explicitly test the predictions of the independent hemifield hypothesis; rather, they focus on testing for deviations from the integrated hemifield hypothesis.

Here, we test the three alternative predictions directly in the context of a dual task with multiple object judgments, which echoes the design of multiple object tracking studies. In both, the two tasks are the same, but applied to different locations. This study is based on previous work showing large divided attention effects for visual object categorization: participants are less accurate when judging the category of two objects at the same time, relative to judging the category of one object (Popovkina et al., 2021). Generally, when having to process multiple stimuli, their spatial location and arrangement can influence performance at both perceptual (e.g. crowding, eccentricity dependence) and attentional levels (e.g., divided attention effects). The dual-task paradigm can mitigate the contribution of the perceptual factors, thereby isolating attentional factors, by using identical displays across conditions and cues to indicate the relevant stimuli. The question remains whether hemifield arrangement modulates the magnitude of the measured divided attention effects, and we test this possibility specifically.

Overview of experiments

In this article, we ask whether presenting object stimuli in separate left and right hemifields modulates the effect of divided attention. The observed hemifield effect is tested against specific predictions of hypotheses proposing independence, integration, or partial dependence of processing in the left and right visual hemifields. Both experiments measure the effect using matched stimulus displays and attentional cueing. Experiment 1 uses a display with four stimuli, arranged with one stimulus in each visual quadrant; Experiment 2 uses a display with two stimuli, arranged either along the horizontal meridian or along the vertical meridian.

Experiment 1: Quadrant design

In the first experiment, the task was semantic object categorization, building on previous work examining divided attention for objects using dual tasks (Popovkina et al., 2021). The stimulus arrangement followed previous work investigating hemifield processing, which placed stimuli in four quadrants of the visual field (top left, top right, bottom left, and bottom right; similar to Alvarez et al., 2012). This design allows for identical stimuli in all conditions. In the current study, the different conditions cued either one or two of the four stimulus locations at a time; when two locations were cued, they were arranged either unilaterally (in the same visual hemifield) or bilaterally (in different visual hemifields).

Methods

Participants

For Experiment 1, 10 paid participants (seven male/three female) were recruited from the University of Washington and greater Seattle community. Participants had normal or corrected-to-normal visual acuity. All participants gave written and informed consent in accordance with the Declaration of Helsinki and the human subjects Institutional Review Board at the University of Washington.

Sample size

To determine the appropriate sample size, we examined data from four previous dual-task experiments using rapid serial visual presentation (RSVP) and masked word stimuli (White et al., 2018; White, Palmer, & Boynton, 2020). In each, participants ($n = 10$) performed judgments of words with similar methods as the current study. A power analysis was used to determine the sample size needed to distinguish the predictions of the fixed-capacity, parallel model and the all-or-none serial model using a paired t-test. This was done for the dual-task deficit and a conditional accuracy measure of response correlation. Our calculations assumed alpha and beta errors of 0.05 (power of 95%). The estimated minimum sample size was five for the dual-task deficit and eight for the conditional accuracy measure. To be conservative, we collected data from 10 participants.

Apparatus and eyetracking

Stimuli were presented on a linearized CRT monitor (Sony GDM-FW900) with a resolution of 1024 × 640 pixels and a 120 Hz refresh rate. The monitor was viewed from a 60 cm distance and had a peak luminance of 90 cd/m^2. Presentation of stimuli was controlled using MATLAB (MathWorks, Inc., Natick, MA, USA) and the Psychophysics Toolbox (Brainard, 1997). An Eyelink 1000 (SR Research, Kanata, ON, Canada) and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002) were used to monitor and enforce fixation during the experiment. A trial was terminated if the participant blinked or moved their eyes outside of a 2° window while stimuli were present on the screen. On average, 0.8% ± 0.2% of trials were terminated due to blinks or apparent eye movements in Experiment 1.

Stimuli

The stimuli were photographs of nameable objects removed from the background context, which were previously used in Popovkina et al. (2021). These stimuli were hand-selected from an internet image search and from the Massive Memory Object Categories image set (Konkle, Brady, Alvarez, & Oliva, 2010). Each image was adjusted to maximize contrast and remove color and was resized to a 100 pixel × 100 pixel square (4.2° × 4.2°).


Figure 1. Example stimuli used in both experiments. All images from the category “food” are shown.

Stimuli were from eight categories: plants, food, clothing, animals, furniture, household devices, transport, and music instruments. Two judges confirmed that all examples were easy to identify and clearly belonged to the assigned category, and not the other categories. Each category had 50 exemplar objects; Figure 1 shows the 50 objects in the category “food.” With eight categories, the stimulus set had a total of 400 objects.

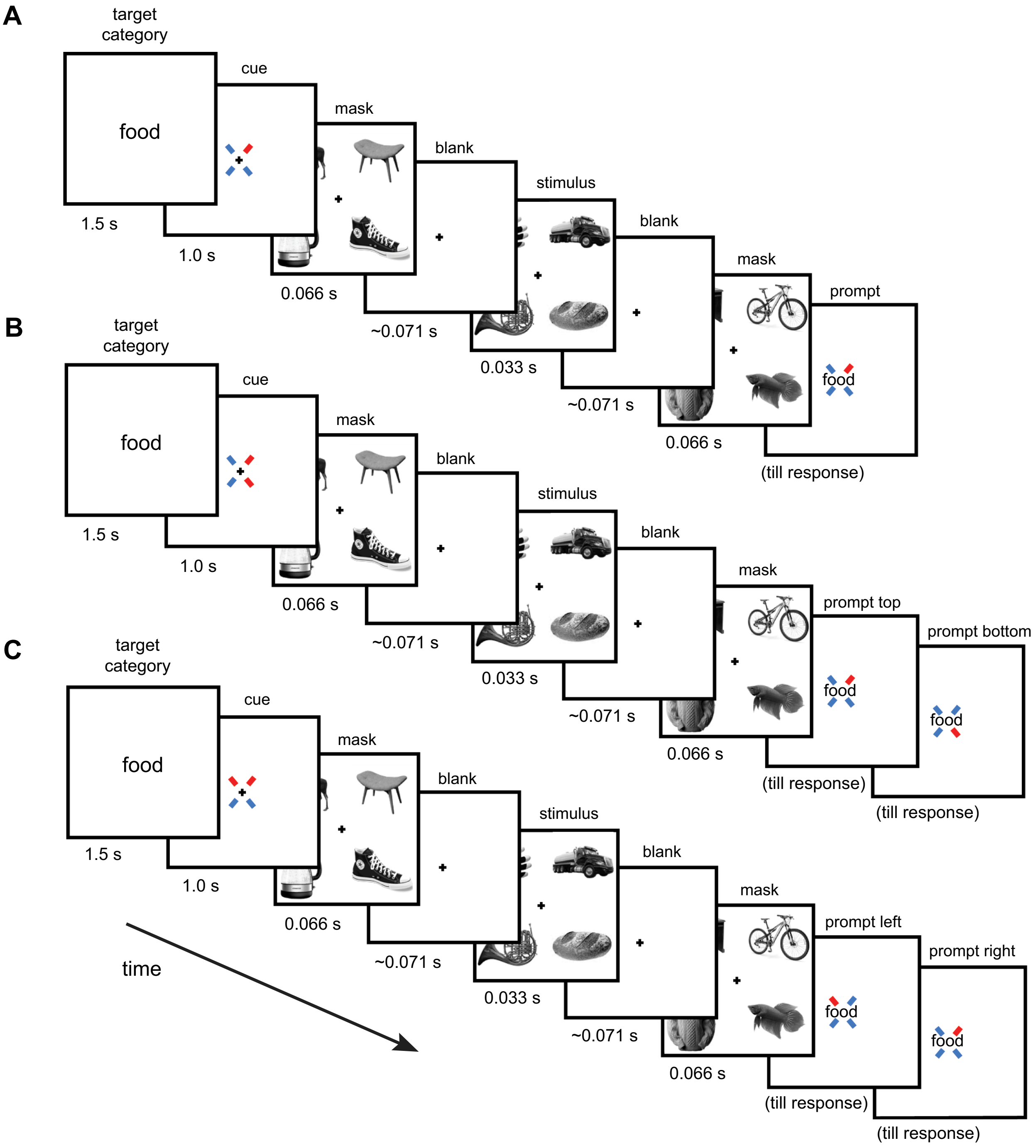

Figure 2. Procedure in Experiment 1. Shown are example trial sequences for the single task (**A**, top right location cued) and dual task (**B**, unilateral: both right locations cued; **C**, bilateral: both top locations cued). In these examples, the observer cue color is red. Mean blank interstimulus interval (ISI) durations shown; these were adjusted separately for each observer to produce ∼80% accuracy in the single task.

Procedure

A schematic of the task is shown in Figure 2. On each trial, the participants saw a word indicating the target category, followed by briefly presented and masked visual objects, and a response prompt. Participants reported with a button press whether an object from the target category had appeared in the cued location. For example, for the trials shown in Figure 2, participants were looking for food objects and a target object (bread) was presented in the bottom right location. The relevant location(s) were cued both before presentation and during the response prompt. Red and blue colored lines were used as cues, with one color assigned as a relevant cue for each participant and the other color serving as the irrelevant cue. The assignment was balanced such that for approximately half of the participants (4/10), the relevant cue was red, and for the others (6/10), the relevant cue was blue. In the example sequence shown in Figure 2, the relevant cue is red.

Stimulus images were presented in four visual quadrants (top left, top right, bottom left, and bottom right); the 4.2° × 4.2° images were centered at 5.66° away from a 0.5° fixation cross. A schematic of an example trial sequence is shown in Figure 2, with each box representing a time interval. The sequence contained 3 object presentation intervals; the first and last object presentations served as pre- and post-masks, and never contained an object from the target category. In the middle presentation interval, objects from the target category could appear with a 50% chance, independently for the four locations. Thus, the presence of a target object in one location gave no information about the presence of a target object in any of the other locations; there could be zero, one, two, three, or four target category objects on the display in a given trial. Target objects shown within a block (16 trials) were unique. Thus, on trials where targets were present in more than one location, no target objects were identical. All nontarget stimuli, including masks, were randomly chosen from nontarget categories. A brief blank display followed the postmask, after which a brief tone accompanied the response prompt.

Conditions

Stimuli were presented in three different conditions, which were blocked:

In the *single-task condition* (Figure 2A), there was a single task to perform on each trial. Objects were presented in four locations, but only one location was cued as relevant. A label at the beginning of a block indicated the relevant location, which stayed the same for the duration of the block. Participants judged only the object in that location.

In the *dual-task conditions* (Figures 2B, 2C), there were two tasks to perform on each trial. As in the single-task condition, objects were presented in four locations, but two locations were cued as relevant and participants judged the objects separately for these two locations. The order of testing the two locations was randomized to prevent response preparation before the prompt. In the unilateral dual-task condition, the two relevant locations were in the same visual hemifield (e.g. Figure 2B: both cued locations in the right hemifield). In the bilateral dual-task condition, the two relevant locations were in different visual hemifields (e.g. Figure 2C: one cued location in the left hemifield and the other cued location in the right hemifield). Diagonal locations were never cued. In other words, for the bilateral dual-task condition, either the two top locations or the two bottom locations were cued.

Timing

Before the main experiment, the duration of the blank interstimulus interval was adjusted for each participant to achieve approximately 80% accuracy in the single-task condition using a manual staircase procedure: in training sessions, we assessed performance in blocks of ∼32 to 64 trials. Durations were long at first and were gradually shortened, with occasional returns to longer durations. If necessary, finer steps around the 80% performance level were reassessed before settling on a final duration value for that participant for the main experiment. The mean interstimulus interval across 10 participants was 71 ms (range, 41 ms to 108 ms), and the resulting mean accuracy was 81.7% ± 1.1% in the single-task condition. For the main experiment, the same individualized timing was used in all conditions for that participant.

Control condition

To verify that the stimuli were discriminable with brief presentation in the periphery, we collected a small additional set of data from single-task trials (32 trials of each of the four cue conditions for nine of the 10 participants; 16 trials of each of the four cue conditions for one other participant). To assess performance while minimizing the effect of masking, a long interstimulus interval (408 ms) was used instead of the duration value titrated for 80% correct performance. With this timing, the average single-task performance was high: 97.3% ± 0.6%. Thus, without an effective mask the participants can perform the single task very well. This result also shows that cueing was effective.

Responses

Participants made unspeeded responses using one of four buttons. They reported “yes”/“no” answers to the core question: “in the prompted location, did any object belong to the target category?” Participants also gave a confidence rating (“likely” or “guess”) associated with their report. Specifically, the four buttons represented the following responses: “likely no,” “guess no,” “guess yes,” and “likely yes.” Each of the four stimulus locations was associated with one of four keypads, arranged in the same fashion as the stimuli (that is, to make a response about the stimulus in the top left location, participants pressed a button on the top left keypad). To minimize the contribution of Simon effects (Simon, Small, Ziglar, & Craft, 1970), some of the participants (4/10) used a vertical button layout, and the other participants (6/10) used a horizontal button layout. In the vertical button layout, the response buttons were arranged in a single column on the keypad; in the horizontal button layout, the response buttons were arranged in a single row on the keypad. After the response, feedback was given in

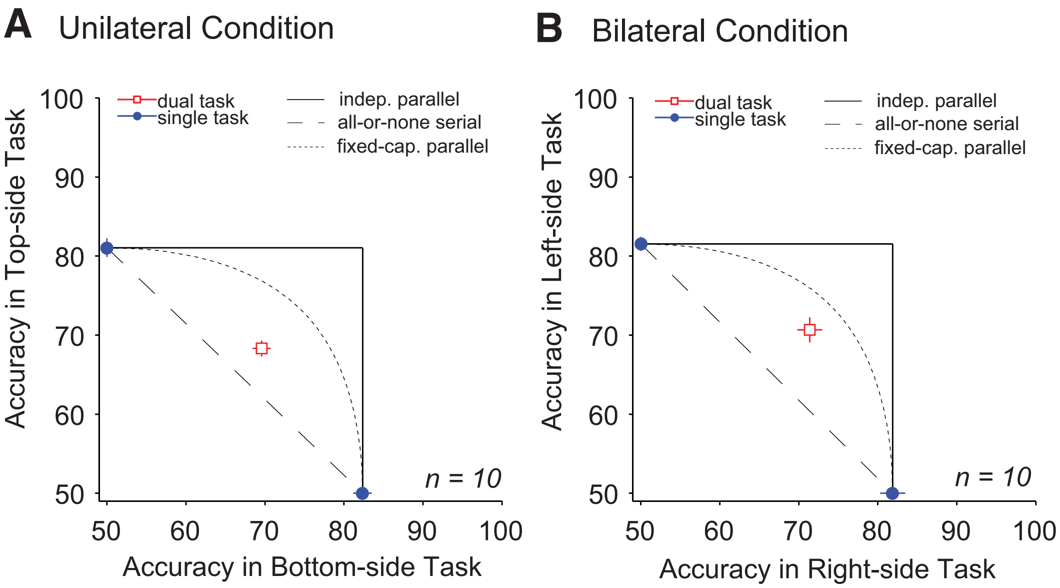

Figure 3. Attention operating characteristic for Experiment 1. Observed accuracy, measured as area under ROC curve, in single (blue) and dual (red) tasks in the unilateral condition (**A**) and bilateral condition (**B**). Error bars are the standard error of the mean. Solid line: prediction of the independent parallel model. Dashed line: prediction of the all-or-none serial model. Dotted curve: prediction of the fixed-capacity parallel model.

the form of a high- or low-frequency tone for correct and incorrect responses, respectively. Feedback for the responses in the dual-task condition was provided only after both responses were given.

Design

The experiment was carried out in sessions of eight blocks of 16 trials: four blocks of single task (one block per each cued location); two blocks of unilateral dual task (one cued to the two left locations, one cued to the two right locations); and two blocks of bilateral dual task (one cued to the two top locations, one cued to the two bottom locations). Trials within each block had the same target category and the order of blocks was randomized for each session. Each session took about 30 minutes to complete. A complete experiment included at least 35 sessions for a total of at least 535 trials per task condition.

Analysis

Accuracy was defined as the percentage of area under the receiver operating characteristic (ROC) constructed using the confidence ratings reported by the participants. This metric has properties similar to two traditional accuracy measures: like percent correct, it is bounded by 50% (chance accuracy) and 100% (perfect accuracy); and, like d', it is an unbiased measure of accuracy. All accuracy results are reported as mean ± standard error of the mean. For significance testing, all tests were two-tailed and alpha levels were set to 0.05. Effect sizes are reported as Cohen's d for t-tests and Cohen's f for analysis of variance.

Main results

Dual-task deficit and hemifield effect

Dual-task performance in the unilateral condition (68.9% ± 1.0%) was lower than the single-task performance (81.7% ± 1.1%), producing a dual-task deficit of 12.8% ± 0.6%. Dual-task performance in the bilateral condition (71.0% ± 1.2%) was also lower than the single-task performance, producing a dual-task deficit of 10.7% ± 0.7%. The difference between the dual-task deficits in these conditions is the hemifield effect, which was 2.1% ± 0.5% and significantly different from zero ($t(9) = 4.07$, $p = 0.003$, $d = 1.29$). Although significant, the magnitude of the observed hemifield effect was less than one fifth of the magnitude of the observed dual-task deficit across the two dual-task conditions (18%). Thus this result was far from the prediction of the independent hemifield hypothesis.

To place the measured divided attention effects in context, we considered the effects predicted by three benchmark processing models. Figure 3 shows average accuracy in the form of an attention operating characteristic (Sperling & Melchner, 1978). Accuracy for the task in the left location (y axis) is plotted against

	Irrelevant target context *(T)*	Irrelevant distractor context *(D)*	*T-D*
Unilateral condition			
Relevant target (hits)	61.1% ± 2.4%	62.9% ± 1.6%	−1.8% ± 1.3%
Relevant distractor (correct rejections)	67.7% ± 2.5%	72.9% ± 2.5%	−5.2% ± 1.5%
Bilateral condition			
Relevant target (hits)	60.3% ± 2.0%	62.2% ± 1.4%	−1.9% ± 1.2%
Relevant distractor (correct rejections)	73.1% ± 2.2%	78.3% ± 1.9%	−5.2% ± 1.6%

Table 1. Percent hit and correct rejection by target or distractor context for Experiment 1.

accuracy for the task in the right location (x axis). The blue circles on the axes indicate the single-task accuracy for the respective locations; the red square indicates accuracy for each of the locations in the dual-task condition. The overlaid lines correspond to the predictions of three benchmark models: the independent parallel model (solid line); the all-or-none serial model (dashed line); and the fixed-capacity parallel model (dotted line); for more detail, see Popovkina et al. (2021). Figure 3A summarizes the results for the unilateral dual-task condition, whereas Figure 3B summarizes the results for the bilateral dual-task condition. In both cases, the observed dual-task deficits are smaller than the prediction of the all-or-none serial model, and larger than the predictions of the parallel models. Thus the hemifield effect was not large enough to change where the observed divided attention effects fall in the context of the benchmark models. The observed hemifield effect was a fraction of the dual-task deficit magnitude, reflecting that it is an important but not major driving contributor to divided attention effects.

Secondary results

We conducted a number of secondary analyses to assess whether hemifield effects might manifest in ways that are more specific than the dual-task deficit modulation reported above.

No difference in two-target effects

To examine whether hemifield processing affects selective attention via context effects, we analyzed two-target effects (where performance is worse in the presence of two targets). We have previously observed such effects for tasks using RSVP, but not for tasks using brief masked displays such as this one (Popovkina et al., 2021). Similar to congruency effects (Navon & Miller, 1987; Yantis & Johnston, 1990), this analysis quantifies a context effect of one location on the other. Performance is examined separately for hits and correct rejections in two contexts: when the irrelevant location contains an object from the target category (“irrelevant target context”), and when the irrelevant location contains an object from any nontarget category (“irrelevant distractor context”). Table 1 presents this analysis separately for unilateral and bilateral conditions.

For hits, the irrelevant target context represents a display with two targets, and performance is expected to be worse than the irrelevant distractor context. This would produce a negative value in the $T - D$ difference column. For correct rejections, two-target effects specific to targets do not have any expected context-dependent differences.

The results were similar for the unilateral and bilateral conditions. Among hits, there was a deficit for the irrelevant target context compared to the irrelevant distractor context (upper right cell), as expected for a two-target effect; however, this effect was not reliable (unilateral: $t(9) = -1.38$, $p = 0.201$, $d = 0.43$; bilateral: $t(9) = -1.53$, $p = 0.161$, $d = 0.48$). Among correct rejections, there was a deficit, which is not consistent with the prediction of a two-target effect (lower right cell; unilateral: $t(9) = -3.39$, $p = 0.008$, $d = 1.07$; bilateral: $t(9) = -3.15$, $p = 0.0117$, $d = 1.00$). A congruency effect or a more general target interference effect that also affects distractors both predict negative values here. These results replicate our previous findings (Popovkina et al., 2021) and suggest the presence of a general target interference effect, or the combination of a two-target and congruency effect for masked displays. Relevant for the present study, there was no difference between unilateral and bilateral conditions.

No difference in effect of response order in the dual task

In the dual task, one of the two locations was randomly chosen as the first response, and the other as the second response. Accuracy for the first response (70.8% ± 1.1%) was similar to accuracy for the second response (69.4% ± 1.2%). The difference was 1.4% ± 0.5% (significantly different from zero, $t(9) = 3.13$, $p = 0.012$, $d = 0.99$), which is small relative to the dual-task deficit. This effect calculated separately for the unilateral condition (1.0% ± 0.8%) and the bilateral condition (2.0% ± 0.6%) showed no significant difference between the conditions ($t(9) = -1.06$, $p = 0.315$, $d = 0.36$).

	Single task		Unilateral dual task		Bilateral dual task	
	Left side	Right side	Left side	Right side	Left side	Right side
Top side	80.8% ± 1.1%	81.3% ± 1.7%	68.6% ± 1.9%	68.0% ± 1.3%	69.9% ± 1.6%	70.7% ± 1.6%
Bottom side	82.3% ± 0.9%	82.5% ± 1.6%	70.6% ± 1.5%	68.6% ± 1.8%	71.4% ± 1.2%	72.1% ± 1.7%

Table 2. Performance per stimulus location (mean ± S.E.M.) in Experiment 1.

Thus memory and response interference appeared to affect the second response to a small extent, but did not contribute substantially to the hemifield effect. This response order effect was not found in Experiment 2 (see below) so we do not pursue it further.

No difference in response correlation

For the case of an all-or-none serial model, dual-task accuracy should be higher for a response in one location if the response in the other location was wrong. In contrast, parallel models predict no difference. One way to quantify such a response correlation is using a difference between conditional accuracy measures in two sets of trials: one set where the response about the other stimulus in the same trial was correct, and another set where the response about the other stimulus in the same trial was wrong (see White et al., 2018; White et al., 2020; Popovkina et al., 2021). In unilateral dual-task trials, the observed conditional accuracy difference was $-1.5\% \pm 1.1\%$ (not significantly different from zero, $t(9) = 1.45$, $p = 0.181$, $d = 0.46$). In bilateral dual-task trials, the observed conditional accuracy difference was $-0.7\% \pm 0.9\%$ (not significantly different from zero, $t(9) = 0.77$, $p = 0.459$, $d = 0.23$). These effects were not significantly different for the unilateral and bilateral conditions ($t(9) = 0.93$, $p = 0.376$, $d = 0.29$). Thus neither condition shows signs of serial processing by this measure.

No effect of stimulus location

Table 2 shows the performance for each of the stimulus locations in each of the task conditions. There were small variations in performance in each location that did not appear to reflect systematic differences. The overall average performance was 73.1% ± 1.4% in the top left location; 73.3% ± 1.3% in the top right location; 74.7% ± 1.1% in the bottom left location; and 74.4% ± 1.6% in the bottom right location. In a two-way analysis of variance (subjects x stimulus location), there was no significant effect of stimulus location ($F(3,27) = 0.68$, $p = 0.57$, $f = 0.27$). Results of analyses using left versus right hemifield or top versus bottom hemifield instead of quadrant location yielded similar results. Thus overall performance was similar in all locations.

Discussion

In summary, in the first experiment, we found a smaller dual-task deficit when the cued stimulus locations were in separate left and right hemifields, relative to when they were in the same hemifield. This modulation of the divided attention effect rejects the integrated hemifield hypothesis, which predicts no such difference. Because there was a dual-task deficit for all relevant stimulus arrangements, our observations also reject the independent hemifield hypothesis, which predicts no dual-task deficit when stimulus locations are in separate hemifields. The magnitude of the hemifield effect (2.1%) was modest relative to the magnitude of the divided attention effect (11.8%). The secondary analyses showed no significant contribution of other factors (such as response order or context effects) to the hemifield effect. Before considering the implications of these results, we present a second version of the experiment to test its generality.

Experiment 2: Meridian design

The second experiment assessed the generality of the observations from Experiment 1 with a different presentation protocol and the common stimulus displays on the horizontal and vertical meridians. We introduced temporal uncertainty using RSVP, reduced the number of stimulus locations from four to two, and arranged the stimuli along the meridians instead of in quadrants. In this experiment, stimuli were presented bilaterally: to the left and right of fixation, along the horizontal meridian. To examine hemifield effects with a comparable condition, we use a previously published experiment with stimuli presented above and below fixation, along the vertical meridian (Popovkina et al., 2021; Experiment 1 in that paper). This condition is clearly not bilateral, but the term ‘unilateral’ is not directly applicable. Thus, we call it the “unilateral-like condition” here. Although conducted at separate times, both experiments used the same equipment, procedures, and participant population.

To measure divided attention effects, our approach compares conditions with identical displays, i.e. comparing cueing one location to cueing two locations.

An alternative approach is to compare a condition with one stimulus displayed to a condition with two stimuli displayed. Both designs have been used in visual search and hemifield studies (compare Kraft et al., 2005 to Luck et al., 1994). The distinction between them is that the latter is vulnerable to additional effects of phenomena such as crowding or flanker effects. Although our general approach has been to avoid these effects, here they are examined using another condition with a single stimulus display.

Methods

The experiment design and methods were similar to Experiment 1, with exceptions elaborated below. Details related to the procedure, conditions, timing, responses, and design were matched between Experiment 2 and the published unilateral-like condition.

Participants

For Experiment 2, 11 paid participants (8 male/3 female) were recruited from the University of Washington and greater Seattle community.

Sample size

Following the same power analysis as for Experiment 1, we estimated a minimum sample size of 10. In practice, we collected data from a total of 11 participants in Experiment 2.

Eyetracking

In Experiment 2, 1.3% ± 0.4% of trials were terminated due to blinks or apparent eye movements.

Procedure

Figure 4 shows a schematic of the semantic categorization task in Experiment 2. This task is a bilateral version of a previously published unilateral-like experiment (Popovkina et al., 2021; Experiment 1). The cue assignment was balanced such that for approximately half of the participants (5/11), the relevant cue was red, and for the other half (6/11), the relevant cue was blue (in Figure 4, the relevant cue is red).

Stimuli were presented to the left and right of a 0.5° fixation cross and the 4.2° × 4.2° images were centered at 4° away from fixation. In Experiment 2, stimuli were presented as an RSVP sequence. A schematic of an example trial sequence is shown in Figure 4, with each box representing a time interval. The RSVP sequence contained 7 object presentations separated by equal duration intervals with a blank screen (only 3 object presentations are shown in the figure). The first and last object presentations never contained an object from the target category (serving as pre- and post-masks). Within the second to sixth intervals, one object from the target category can appear amid a stream of objects from other categories. Over the course of the entire sequence, there was a 50% chance of a single target object appearing within the stream at a given stimulus location, and a 50% chance of no target objects appearing within the stream at a given stimulus location. This probability was independent for the two locations: that is, the presence of a target object in one location gives no information about the presence of a target object in the other location. The only dependency between locations was that in trials with a target present in both locations, the targets appeared in the same interval to make switching ineffective. All other stimuli, including masks, were randomly chosen from nontarget categories. The post-mask stayed on the screen for 700 ms, at which time a brief tone accompanied the response prompt. The post-mask was replaced by a blank as soon as there was a response.

Conditions

Stimuli were presented in three different conditions, which were blocked:

In the *single-task condition* (Figure 4A), objects were presented in two locations, but only one location was relevant. A label at the beginning of a block indicated whether the relevant location was on the left or the right side of the display; the relevant location stayed the same for the duration of the block. Participants judged the object in the cued location only.

In the *dual-task condition* (Figure 4B), there were two tasks to perform on each trial. Again, objects were presented in two locations, but both locations were relevant and participants judged the objects separately for each location. The order of testing the two locations was randomized.

In the control *single-stimulus condition* (Figure 4C), there was a single task to perform on each trial. Participants saw an object in only one location and judged the object in that location. The relevant location stayed the same for the duration of the block. The only difference from the single-task condition was the absence of the irrelevant stimulus. This condition was included to check for crowding and similar interference effects.

Timing

Before the main experiment, the RSVP timing was adjusted for each participant to achieve approximately 80% accuracy in the single-task condition by manipulating the duration of the stimulus and blank intervals using a manual staircase procedure as in

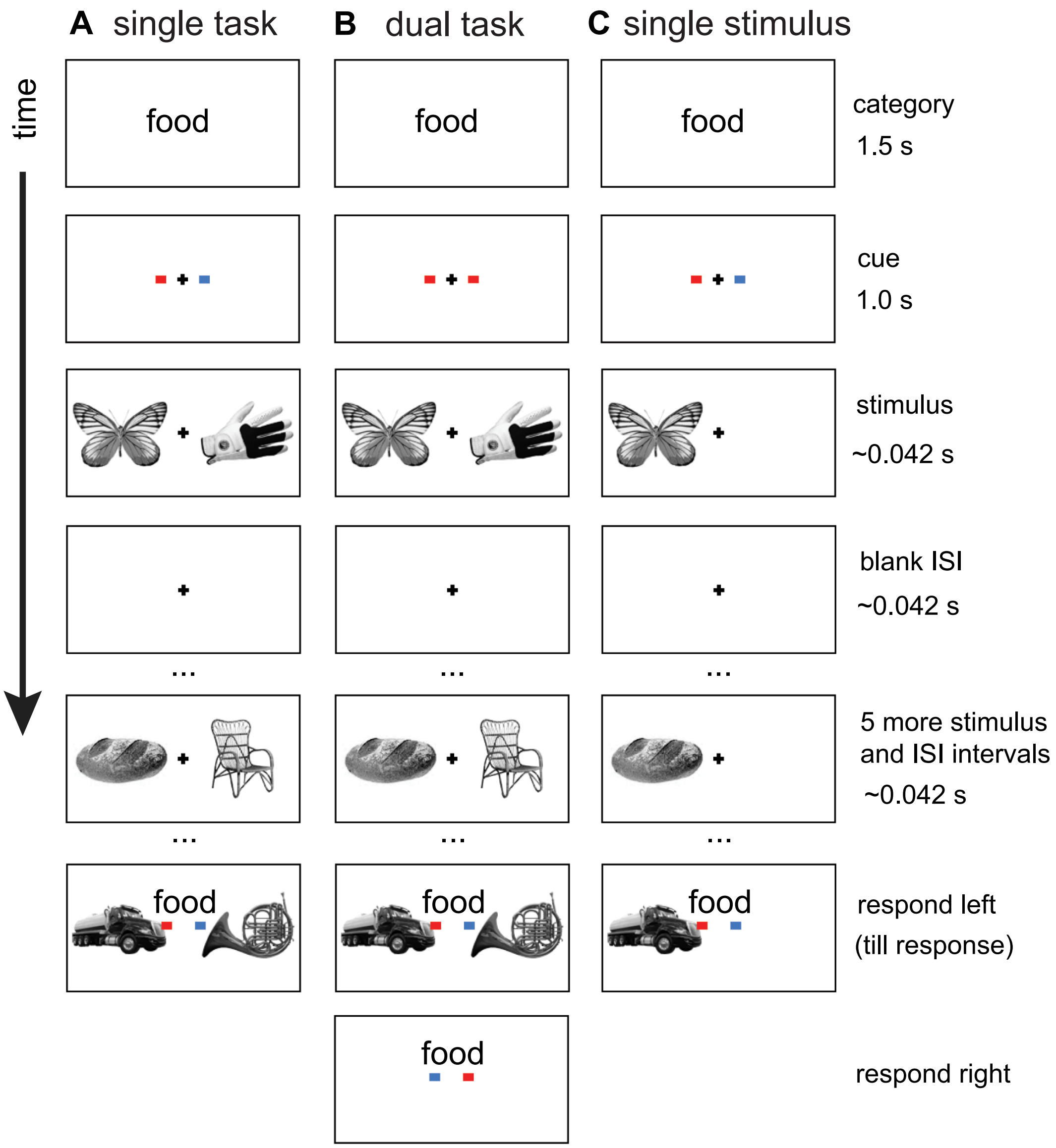

Figure 4. RSVP procedure in Experiment 2. Trial sequences for the single task (**A**, left location cued), dual task (**B**, both locations cued), and single stimulus display condition (**C**, left location) are shown. Ellipses indicate more intervals of the same duration, for a total of seven intervals containing objects and six intervening blank intervals. In this example, the observer cue color is red. Mean stimulus and blank ISI durations shown; these were adjusted separately for each observer to produce ∼80% accuracy in the single task.

Experiment 1. The stimulus and interval durations were always identical, and adjusted together. The mean stimulus and interval duration across 11 participants was 36 ms (range 25 ms–41 ms), and the resulting mean accuracy was 79.5% ± 1.7% in the single-task condition. For the main experiment, the same customized timing was used in all conditions for a given participant.

Responses

As in Experiment 1, participants used four buttons to indicate “yes”/“no” responses and “likely”/”guess” confidence ratings. Response button layout was vertical, orthogonal to the horizontal stimulus layout. Responses about the left location were arranged along the leftmost column of a keypad; responses about the right location were arranged along the rightmost column of a keypad.

Design

The experiment was carried out in sessions of six blocks of 16 trials: two blocks of dual task; two blocks of single task, one cued to the left location and one cued to the right location; two blocks of single stimulus, one cued to the left location and one cued to the right location. Trials within each block had the same target category and the order of blocks was randomized for each session. Each session took about 15 minutes to

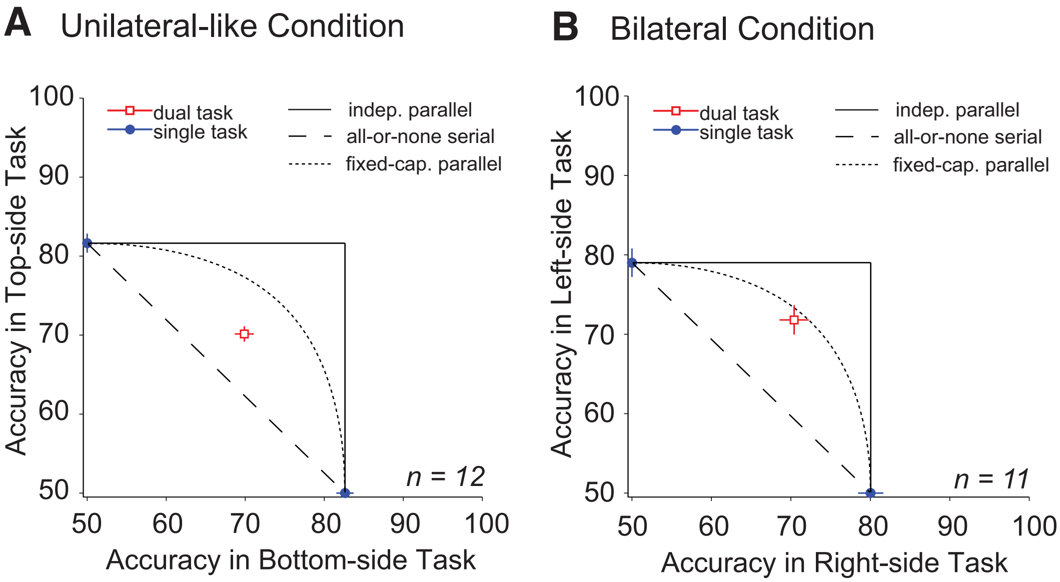

Figure 5. Attention operating characteristic for Experiment 2. Observed accuracy, measured as area under ROC curve, in single (blue) and dual (red) tasks in the unilateral-like condition (**A**, reproduced from Popovkina et al., 2021) and bilateral condition (**B**, current study). Error bars are the standard error of the mean. Solid line: prediction of the independent parallel model. Dashed line: prediction of the all-or-none serial model. Dotted curve: prediction of the fixed-capacity parallel model.

complete. A complete experiment included at least 38 sessions for a total of at least 1200 trials per condition.

Main results

Dual-task deficit and hemifield effect

Accuracy in the dual-task condition (71.1% ± 1.7%) was worse than in the single-task condition (79.5% ± 1.7%), producing a dual-task deficit of 8.4% ± 0.9% (significantly different from zero, $t(10) = 9.8$, $p < 0.001$, $d = 2.95$). This deficit is a bilateral dual-task deficit; the corresponding unilateral-like dual-task deficit (12.1% ± 1.0%) was reported in Experiment 1 of Popovkina et al. (2021). The difference between these two deficits is the hemifield effect: 3.7% ± 1.4% (significantly different from zero, $t(21) = 2.81$, $p = 0.011$, $d = 0.60$, two-sample t-test). Relatively, the magnitude of the observed hemifield effect was just over one third of the magnitude of the observed dual-task deficit across the two dual-task conditions (36.1%).

Attention operating characteristics (Sperling & Melchner, 1978) are shown in Figure 5. Figure 5A shows the results for the unilateral-like condition, reproduced from Popovkina et al. (2021), whereas Figure 5B shows the results for the bilateral condition, from the current experiment. Both of the results are inconsistent with the independent parallel model and the all-or-none serial model. The results for the bilateral condition are similar to the magnitude of dual-task deficit predicted by the fixed-capacity parallel model. As in Experiment 1, the hemifield effect was not large enough to substantially change where the observed divided attention effects fell in the context of the benchmark models: in both conditions, the divided attention effect was intermediate. Again, as in Experiment 1, the hemifield effect was a fraction of the dual-task deficit magnitude.

Small difference in effect of the second stimulus

In the single-stimulus condition, participants performed the single task with stimuli presented in only the relevant location. The difference between the accuracy in the single-stimulus condition and the single-task condition was small in magnitude (2.6% ± 0.5%) but significantly different from zero ($t(10) = 5.81$, $p < 0.001$, $d = 1.75$), suggesting that there was a small performance deficit due to adding a second stimulus on the screen along the horizontal meridian. In the published unilateral-like condition, the effect of the second stimulus was 0.9% ± 0.5% (not significantly different from zero, $t(11) = 1.98$, $p = 0.073$, $d = 0.57$), suggesting that there was little or no change in performance with the addition of a second stimulus on the screen along the vertical meridian. There was a significant difference of 1.7% between the unilateral-like and bilateral conditions ($t(21) = -2.71$, $p = 0.013$, $d = 0.58$, two-sample t-test). Thus there is some evidence of a stimulus-driven effect that causes a bilateral disadvantage. This finding is consistent with

	Irrelevant target context *(T)*	Irrelevant distractor context *(D)*	*T–D*
Unilateral-like condition (Popovkina et al., 2021)			
Relevant target (hits)	57.0% ± 1.3%	62.8% ± 1.6%	−5.8% ± 1.3%
Relevant distractor (correct rejections)	72.5% ± 1.8%	75.7% ± 2.4%	−3.1% ± 1.7%
Bilateral condition (present study)			
Relevant target (hits)	58.0% ± 2.4%	61.9% ± 2.8%	−3.9% ± 1.5%
Relevant distractor (correct rejections)	75.6% ± 2.3%	79.2% ± 2.3%	−3.5% ± 1.8%

Table 3. Percent hit and correct rejection by target or distractor context for Experiment 2.

previous studies where this effect was always smaller than the dual-task deficit (Popovkina et al., 2021).

Secondary results

No difference in two-target effects

Table 3 summarizes the results of the two-target effect analysis, first reproducing the published unilateral-like condition and then presenting the analysis for the bilateral condition in Experiment 2.

The results were similar for both the unilateral-like and the bilateral condition. Among hits, there was a reliable deficit for the irrelevant target context compared to the irrelevant distractor context, as expected for a two-target effect (upper right cell; unilateral-like: $t(11) = -4.51$, $p < 0.001$, $d = 1.30$; bilateral: $t(10) = -2.69$, $p = 0.0227$, $d = 0.81$). Among correct rejections, there was a small but unreliable deficit, which is harder to interpret (lower right cell; unilateral-like: $t(11) = -1.80$, $p = 0.100$, $d = 0.52$; bilateral: $t(10) = -1.94$, $p = 0.0812$, $d = 0.58$). A two-target effect that is specific to targets should produce no difference, but a congruency effect or a more general target interference effect that also affects distractors both produce expected negative values. Consequently, based on this cell one cannot distinguish a congruency effect from a more general target interference effect. Overall, there was no difference between unilateral-like and bilateral conditions.

No difference in effect of stimulus order in the RSVP sequence

There was a small advantage for detecting a target object in the first possible stimulus interval (73.5% ± 1.5%) compared to the last possible stimulus interval (71.2% ± 1.6%). This difference was small (2.3%±1.2%) and not significantly different from zero ($t(10) = 1.85$, $p = 0.094$, $d = 0.56$). There was a similar result in the published unilateral-like condition (2.4% ± 1.3%; $t(11) = 1.83$, $p = 0.094$, $d = 0.53$). Such small “primacy” effects are often reported for RSVP procedures (Coltheart, 1999), and there was no significant difference between the bilateral and unilateral-like conditions.

No difference in effect of response order in the dual task

In the dual task, one of the two locations was randomly chosen as the first response, and the other as the second response. The difference in accuracy for the first and second responses was 1.1% ± 0.6% (not significantly different from zero, $t(10) = 2.05$, $p = 0.068$, $d = 0.62$). There was a similar result in the published unilateral-like condition (0.04% ± 0.8%; $t(11) = 0.049$, $p = 0.96$, $d = 0.01$). Thus neither memory nor response interference appeared to differentially affect the second response for either the bilateral or the unilateral-like condition.

No differences in response correlation

In Experiment 2, the conditional accuracy was higher when the response on the other side was wrong (71.8%) than when the response on the other side was correct (70.0%), a difference of −1.8% ± 0.8% (not significantly different from zero, $t(10) = -2.10$, $p = 0.062$, $d = 0.63$). In the published unilateral-like condition, there was also a small conditional accuracy difference of −2.5% ± 1.1%, which was significantly different from zero ($t(11) = -2.24$, $p = 0.046$, $d = 0.65$). However, these correlations were not significantly different between the two conditions ($t(21) = -0.53$, $p = 0.600$, $d = 0.11$; two-sample t-test). Thus there was no evidence of serial processing in either condition based on this measure.

No effect of stimulus location

The difference in performance for stimuli in the left versus the right locations was 0.2% ± 1.3% (not significantly different from zero, $t(10) = 0.15$, $p = 0.89$, $d = 0.05$). In the published unilateral-like condition, the difference in performance for stimuli in the top versus the bottom locations was 0.4% ± 1.2% (not significantly different from zero, $t(11) = -0.29$, $p = 0.78$, $d = 0.08$). Thus there was no effect of stimulus location in either condition.

Discussion

In summary, in the second experiment, we again found a smaller dual-task deficit when the stimulus locations were in separate left and right hemifields, relative to when they were not in separate hemifields. This finding rejects both the integrated hemifield hypothesis and the independent hemifield hypothesis. The magnitude of the hemifield effect (3.7%) was modest relative to the magnitude of the divided attention effect (10.3%). The secondary analyses showed no substantial contribution of other factors to this effect, with the exception of a 2.6% effect of an irrelevant second stimulus.

Our previous work with the two-stimulus display above and below fixation has also shown a one to two percentage-point reduction in performance for judging one stimulus when an irrelevant second stimulus is present versus absent from the screen (Popovkina et al., 2021). This effect might be due to crowding because the use of a mask increases the spatial extent of crowding (Vickery, Shim, Chakravarthi, Jiang, & Luedeman, 2009). Our finding is consistent with a previous study that shows a stronger crowding effect for stimuli arranged horizontally than vertically (Feng, Jiang, & He, 2007) and with other studies reporting horizontal-vertical asymmetries (e.g., Mackeben, 1999; Chakravarthi, Papadaki, & Krajnik, 2022). Because we use matched displays with attentional cueing, the measurement of how much hemifields modulate divided attention effects is unlikely to be affected by this factor. More generally, this observed difference between horizontal and vertical arrangements raises the question of whether crowding or other spatial interactions might contribute to hemifield effects in the larger world of multiple stimulus judgments that do not use identical stimuli in all conditions.

Overall, the results of Experiments 1 and 2 were similar and rejected two of the three alternative hypotheses. These results support the third alternative hypothesis: that visual processes in the left and right hemifields are partially dependent for divided attention tasks with object judgments.

General discussion

Summary of results

In this study, we asked whether the effect of divided attention is modulated by visual hemifields. In two experiments, we used a dual-task paradigm with relevant object locations either in the same or different hemifields, and found a small but reliable hemifield effect. Specifically, the dual-task deficit was smaller but not eliminated when the stimuli to be judged were placed in separate left and right hemifields. This result is consistent with neither the independent hemifield hypothesis, nor with the integrated hemifield hypotheses. Instead, it is consistent with the hypothesis that hemifields are partially dependent. The magnitude of the hemifield effect was modest relative to the magnitude of the divided attention effect; on average across the two experiments, it was about a quarter (27%) of the dual-task deficit. This effect is closer to the integrated hemifield hypothesis prediction than the independent hemifield hypothesis prediction.

Assuming a direct relationship between hemifield effect and degree of process dependency between the two hemifields, we can use our measurement of the former to estimate the latter. The independent hemifield hypothesis (0% dependent) predicts that divided attention effects should be eliminated in the bilateral presentation (i.e., hemifield effect = 100% of the dual-task deficit). The integrated hemifield hypothesis (100% dependent) predicts that divided attention effects should be identical in the unilateral and bilateral presentations (i.e., hemifield effect = 0% of the dual-task deficit). Our observed hemifield effect is about a quarter of the size of the dual-task deficit; thus, for dual-tasks with object judgments, about three quarters of the processes dependent in a dual task are shared between the left and right hemifields.

In addition to the hemifield effect on divided attention, we found some evidence for a small stimulus-driven effect of irrelevant stimuli in the second experiment. This effect was stronger in the bilateral than the unilateral conditions, consistent with previous work on such asymmetries (Feng et al., 2007; Mackeben, 1999; Chakravarthi et al., 2022). These effects are interesting in themselves, but importantly, they are distinct phenomena from the larger hemifield effects on divided attention.

Relationship to other hemifield effect studies

One way in which the current study stands apart from previous work in visual search is that it allows for a specific test of the independent hemifield hypothesis in addition to testing for divergence from the integrated hemifield hypothesis. Such a test in not always possible in visual search paradigms. However, in the dual-task paradigm used here, it is possible to test specific independent and integrated hypothesis predictions. Moreover, this paradigm is comparable to multiple object tracking tasks and thus we can interpret our results in the context of their findings as well.

Alvarez et al. (2012) propose that there is independent processing in visual search tasks with a multifocal spatial attention component, but not in typical visual search tasks. Importantly, our dual task design required the participants to divide attention between two spatial locations and ignore other locations. To make each response in a dual-task trial, participants had to select the relevant spatial location and ignore the other location. These concurrent selective attention tasks necessitate multifocal spatial attention. Further, we specify and test distinct predictions of the three alternative hypotheses for hemifield independence. The predictions for these hypotheses are less clear in the visual search paradigm; while the results in Alvarez et al. (2012) show clear deviation from the prediction of the integrated hemifield hypothesis, it's possible that their result falls in the same intermediate territory as ours, namely consistent with the predictions of the partially dependent hemifield hypothesis. Luck et al. (1994) lay out a distinct prediction for the independent hemifield hypothesis in visual search based on a simple serial model of processing: the slope, measured as the slope of response time as a function of set size, should be twice as steep in the unilateral condition as in the bilateral condition. The results of the experiment in Alvarez et al. (2012) fall short of this prediction, consistent with the interpretation that the hemifields are partially dependent.

There are other precedents of the current study which focus on hemifield effects of divided attention for object-based judgments, including Awh and Pashler (2000) and Chakravarthi and Cavanagh (2009). The latter is the closest precedent to the current study, using a dual task with crowded stimuli and judgments of rotated Ts arranged in the same or different hemifields. The authors identified and tested the distinct predictions of the integrated and independent hypotheses. In one study, they observed intermediate results that rejected both the integrated and the independent hemifield hypotheses. In a second study, they also observed intermediate results, but could not reject the independent hemifield hypothesis. Thus we consider Chakravarthi and Cavanagh (2009) to be consistent with the present study, which also produced intermediate results.

A striking difference between our results and previous work lies in the comparison between our study and studies of multiple object tracking. While two object targets in separate hemifields can be tracked nearly as well as one (Alvarez & Cavanagh, 2005), two objects in separate hemifields cannot be categorized as well as one. One interpretation is that the large hemifield effect for multiple object tracking and the small hemifield effect for object judgments reflect fundamental differences in the processing requirements for these tasks. Hudson, Howe, and Little (2012) argue that the need to identify the object is a source of hemifield dependency that is absent in traditional multiple object tracking tasks. When participants have to judge the identity as well as the location of targets, their performance is consistent with the prediction of partially dependent hemifields, offering a bridge between multiple object tracking and object recognition results. We consider other possible sources of hemifield effects in the next section.

What is the source of hemifield effects?

The results of the current study suggest that while not all processing is independent across hemifields, some aspect of processing is independent. Here, we consider three alternative hypotheses regarding which aspect of processing might be independent across hemifields, and thus lead to the observed modulation of divided attention effects.

Independent processing in perception

One possibility is that hemifield effects arise from independent perceptual processes. By this hypothesis, the underlying architecture of the visual system might be the source of hemifield effects. Cohen et al. (2016) argue that receptive field structure contributes to interactions in processing across the visual field. They compare bilateral and unilateral presentation of various stimuli (e.g. objects, colored squares) and argue that observed hemifield effects can be explained by the spatial interference of trying to encode two stimuli that fall in the same receptive field. Object stimuli presented in the same hemifield in our study could have fallen in the same receptive field for neurons in object-selective regions of the human brain such as lateral occipital cortex. In this area, population receptive fields located at 4°-5° eccentricity are estimated to span 4° to 6° (Amano, Wandell, & Dumoulin, 2009). Our observation that the left and right hemifields are partially dependent suggests that receptive fields located in the right visual hemifield that overlap the left visual hemifield might be contributing to our hemifield effect. Importantly, this account also predicts an identical effect with one relevant and one irrelevant stimulus. We found some evidence of this in the single-stimulus condition in Experiment 2.

Independent processes in working memory

Another possibility is that hemifield effects arise from some degree of independent processing related to visual working memory. By this hypothesis, independent memory capacity in the two hemifields can produce a hemifield effect. Importantly, this possible source might capture the difference between our observations and multiple object tracking, since multiple object tracking occurs over an extended time, explicitly requiring memory maintenance. For object location, working memory capacity for spatial locations is independent for the left and right hemifields: in a location change detection task, working memory capacity increased when stimuli were arranged bilaterally (Delvenne, 2005). This finding supports the possibility that visual working memory processes contribute to the hemifield effects observed in multiple object tracking. For object characteristics, the results are mixed. Umemoto, Drew, Ester, and Awh (2010) used a task with recall of object orientation and simultaneous-sequential displays, and report that hemifield effects can be explained on the basis of more items encoded into working memory in the bilateral than the unilateral condition. In contrast, for an object identity task such as object change detection, a visual working memory account is insufficient: Cohen et al. (2016) report that hemifield effects present in a simultaneous presentation display are eliminated in a sequential presentation display. This finding argues against the involvement of working memory, and in favor of sensory encoding processes contributing to the hemifield effect for their object-based tasks. In summary, there is evidence that both perceptual and memory processes contribute to hemifield effects.

Independent selective attention

A third possibility is that hemifield effects arise from independent selective attention processes acting on perception or memory. By this hypothesis, successful selective filtering of irrelevant stimuli in attended spatial locations might be the source of hemifield effects. For example, Holt and Delvenne (2014) manipulated selective attention in a color change detection task, showing that hemifield effects were present only for displays containing both targets and distractors, and not for displays containing targets alone. This observation was true both for spatial cueing and feature-based cueing. Alvarez et al. (2012) observed similar results only for spatial and not for feature-based cueing. As another example, Störmer, Alvarez, and Cavanagh (2014) present evidence supporting the idea that target processing during multiple object tracking is independent beginning from the earliest stages of sensory processing. As one explanation for why the effects emerge so early, the authors posit that there is an independent attentional focus in each hemifield that is in turn limited to serially processing targets within the hemifield. Thus their results are consistent with selective attention processes that are independent across, but not within, hemifields.

In summary, three sources of hemifield effects—independent perception, independent working memory, and independent selective attention—could underlie our observations for dual tasks with objects. At present, the independent selective attention account seems to be the most consistent with the evidence.

Relationship to visual field asymmetries

Many past studies have revealed visual field asymmetries in task performance, including both perceptual phenomena and attentional phenomena. For example, stimulus location in the visual field affects performance in orientation discrimination. For isoeccentric locations, better performance is observed for locations along the horizontal meridian than locations along the vertical meridian, and for locations in the lower portion than locations in the upper portion of the vertical meridian (Carrasco, Talgar, & Cameron, 2001). As another example, attentional cueing can modulate hemifield asymmetries in word recognition, where performance is typically better in the right visual field. In a task where two spatial locations could contain a word target, there is a smaller right visual field advantage in valid-cue trials and a larger right visual field advantage in invalid-cue trials, relative to neutral-cue trials (Nicholls & Wood, 1998). We don't see evidence of these phenomena in the current study: for example, there is no effect of stimulus location. This is possibly because of the choice of task, or because the task had constant displays. In the larger world of understanding multiple stimulus judgments, it is likely that both hemifield effects and visual field asymmetries make distinct contributions to performance differences.

Conclusions

In this study, we examined how processing in the left and right hemifields modulates divided attention effects for object judgments. Unlike most previous studies, our methods allow a test of both the independent and the integrated hypothesis predictions. In two experiments, we found that divided attention effects were reduced, but not eliminated when stimuli were in separate hemifields relative to when stimuli were not in separate hemifields. These results are consistent with the prediction of partial dependence, where some but not all processing is shared between the hemifields. These results reject both the integrated and the independent hemifield hypotheses. Furthermore, the size of the hemifield effect was closer to the prediction of the integrated than the independent hypothesis prediction. In conclusion, hemifield processing modestly modulates the effects of divided attention in dual tasks with objects.

Keywords: hemifield effect, bilateral advantage, dual task, object categorization

Acknowledgments

The authors thank Justin Harshman for assistance in collecting these data.

Supported in part by grants from the National Eye Institute (F32 EY030320 to D.V.P. and EY12925 to G.M.B. and J.P.).

The data reported in this article are available in the Open Science Framework repository (https://osf.io/nv9pb/).

Commercial relationships: none.

Corresponding author: Dina V. Popovkina.
Email: dina4@uw.edu.
Address: Department of Psychology, University of Washington, 119A Guthrie Hall Box 351525, Seattle, WA 98195-1525, USA.

References

Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychological Science, 16*(8), 637–643.

Alvarez, G. A., Gill, J., & Cavanagh, P. (2012). Anatomical constraints on attention: Hemifield independence is a signature of multifocal spatial selection. *Journal of Vision, 12*(5), 9–9, https://doi.org/10.1167/12.5.9.

Amano, K., Wandell, B. A., & Dumoulin, S. O. (2009). Visual field maps, population receptive field sizes, and visual field coverage in the human MT+ complex. *Journal of Neurophysiology, 102*(5), 2704–2718.

Awh, E., & Pashler, H. (2000). Evidence for split attentional foci. *Journal of Experimental Psychology: Human Perception and Performance, 26*(2), 834.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Carrasco, M., Talgar, C. P., & Cameron, E. L. (2001). Characterizing visual performance fields: Effects of transient covert attention, spatial frequency, eccentricity, task and set size. *Spatial Vision, 15*(1), 61–75.

Chakravarthi, R., & Cavanagh, P. (2009). Bilateral field advantage in visual crowding. *Vision Research, 49*(13), 1638–1646.

Chakravarthi, R., Papadaki, D., & Krajnik, J. (2022). Visual field asymmetries in numerosity processing. *Attention, Perception, & Psychophysics, 84*(8), 2607–2622.

Cohen, M. A., Rhee, J. Y., & Alvarez, G. A. (2016). Limits on perceptual encoding can be predicted from known receptive field properties of human visual cortex. *Journal of Experimental Psychology: Human Perception and Performance, 42*(1), 67.

Coltheart, V. (Ed.). (1999). *Fleeting memories: Cognition of brief visual stimuli*. New York, NY: MIT Press.

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The Eyelink Toolbox: Eye tracking with MATLAB and the Psychophysics Toolbox. *Behavior Research Methods, Instruments, & Computers, 34*(4), 613–617.

Delvenne, J. F. (2005). The capacity of visual short-term memory within and between hemifields. *Cognition, 96*(3), B79–B88.

Feng, C., Jiang, Y., & He, S. (2007). Horizontal and vertical asymmetry in visual spatial crowding effects. *Journal of Vision, 7*(2), 13–13, https://doi.org/10.1167/7.2.13.

Holcombe, A. O., & Chen, W. Y. (2012). Exhausting attentional tracking resources with a single fast-moving object. *Cognition, 123*(2), 218–228.

Holt, J. L., & Delvenne, J. F. (2014). A bilateral advantage in controlling access to visual short-term memory. *Experimental Psychology, 61*(2), 127–133.

Hudson, C., Howe, P. D., & Little, D. R. (2012). Hemifield effects in multiple identity tracking. *PLoS ONE, 7*, e43796.

Konkle, T., Brady, T. F., Alvarez, G. A., & Oliva, A. (2010). Conceptual distinctiveness supports detailed visual long-term memory for real-world objects. *Journal of Experimental Psychology: General, 139*(3), 558.

Kraft, A., Müller, N. G., Hagendorf, H., Schira, M. M., Dick, S., Fendrich, R. M., . . . Brandt, S. A. (2005). Interactions between task difficulty and hemispheric distribution of attended locations: Implications for the splitting attention debate. *Cognitive Brain Research, 24*(1), 19–32.

Luck, S. J., Hillyard, S. A., Mangun, G. R., & Gazzaniga, M. S. (1994). Independent attentional scanning in the separated hemispheres of split-brain patients. *Journal of Cognitive Neuroscience, 6*(1), 84–91.

Mackeben, M. (1999). Sustained focal attention and peripheral letter recognition. *Spatial Vision, 12*(1), 51–72.

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 13*(3), 435.

Nicholls, M. E., & Wood, A. G. (1998). The contribution of attention to the right visual field advantage for word recognition. *Brain and Cognition, 38*(3), 339–357.

Popovkina, D. V., Palmer, J., Moore, C. M., & Boynton, G. M. (2021). Is there a serial bottleneck in visual object recognition?. *Journal of Vision, 21*(3), 15–15, https://doi.org/10.1167/jov.21.3.15.

Sereno, A. B., & Kosslyn, S. M. (1991). Discrimination within and between hemifields: A new constraint on theories of attention. *Neuropsychologia, 29*(7), 659–675.

Simon, J. R., Small, A. M., Ziglar, R. A., & Craft, J. L. (1970). Response interference in an information processing task: Sensory versus perceptual factors. *Journal of Experimental Psychology, 85*(2), 311.

Sperling, G., & Melchner, M. J. (1978). The attention operating characteristic: Examples from visual search. *Science, 202*(4365), 315–318.

Störmer, V. S., Alvarez, G. A., & Cavanagh, P. (2014). Within-hemifield competition in early visual areas limits the ability to track multiple objects with attention. *Journal of Neuroscience, 34*(35), 11526–11533.

Umemoto, A., Drew, T., Ester, E. F., & Awh, E. (2010). A bilateral advantage for storage in visual working memory. *Cognition, 117*(1), 69–79.

Vickery, T. J., Shim, W. M., Chakravarthi, R., Jiang, Y. V., & Luedeman, R. (2009). Supercrowding: Weakly masking a target expands the range of crowding. *Journal of Vision, 9*(2), 12–12.

White, A. L., Runeson, E., Palmer, J., Ernst, Z. R., & Boynton, G. M. (2017). Evidence for unlimited capacity processing of simple features in visual cortex. *Journal of Vision, 17*(6), 19, https://doi.org/10.1167/17.6.19.

White, A. L., Palmer, J., & Boynton, G. M. (2018). Evidence of serial processing in visual word recognition. *Psychological Science, 29*(7), 1062–1071.

White, A. L., Palmer, J., & Boynton, G. M. (2020). Visual word recognition: Evidence for a serial bottleneck in lexical access. *Attention, Perception, & Psychophysics, 82*(4), 2000–2017.

Yantis, S., & Johnston, J. C. (1990). On the locus of visual selection: Evidence from focused attention tasks. *Journal of Experimental Psychology: Human Perception and Performance, 16*(1), 135.