Spatial selectivity in visual detection suffers when attention is divided

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Abstract

Humans are not perfect at selectively responding to one stimulus while ignoring others that are visible at the same time. In *spatial filtering tasks*, this imperfect selectivity is often measured by how the judgment of the relevant stimulus depends on whether an irrelevant stimulus is associated with the same response. Such *congruency effects* decline with increasing spatial separation between stimuli and are minimal for widely separated stimuli. However, there is evidence that divided attention can increase congruency effects even for widely separated stimuli, which is unexpected for typical theories of selective attention. We investigated this possibility for a pair of widely separated detection tasks. Performance was measured under single-task and dual-task conditions. With a single task, there were only small congruency effects, whereas in the dual-task condition larger congruency effects occurred despite the widely separated stimuli. Results from a second experiment with sequential and simultaneous presentations were consistent with the congruency effect being due to later processes such as memory or decision rather than immediate processes such as perception. Additional results comparing high and low performance levels were consistent with congruency effects being due to a graded process such as attenuation or crosstalk rather than an all-or-none process such as blocking or substitution. These results rule out many possible theories of spatial selectivity. Our working hypothesis is that spatial selection can protect against interactive processing of multiple stimuli for a single task but not for dual tasks.

Significance

In visual perception, spatial selectivity is the ability to respond correctly to one stimulus without being influenced by other stimuli presented at the same time. We show that spatial selectivity is reduced when one must attend to multiple stimuli rather than a single stimulus. In other words, while one may be able to focus attention narrowly on a single stimulus, trying to simultaneously attend multiple stimuli can reduce performance due to interference between the attended stimuli. These results inform theories of both selective attention and divided attention

What determines the spatial selectivity of visual perception? Spatial selectivity can be measured using congruency effects in a spatial filtering paradigm. When observers are presented with a relevant stimulus and an irrelevant stimulus simultaneously, congruency effects are the difference in performance between trials in which the stimuli are associated with the same response and trials in which the stimuli are associated with different responses. Such congruency effects are common in studies of the limits of selective attention using spatial filtering (e.g., Eriksen & Hoffman, 1973; Yantis & Johnston, 1990; Y[redacted]). Consider the early example of congruency effects in spatial filtering by Eriksen and Hoffman (1973). They presented a circular display of letters: from the set {A, U} or from the set {H, M}. They cued one location and asked observers to categorize the letter at that cued location into one of the two possible sets while ignoring letters at other locations. They analyzed performance as a function of whether nearby letters were from the same set as the target *(congruent)* or from the other set *(incongruent)*. Responses to targets with congruent neighbors were faster than responses to targets with incongruent neighbors. Moreover, responses to trials with incongruent neighbors that were immediately adjacent to targets were slower than those on which the incongruent neighbors were further away. This modulation reveals spatial selectivity.

In this article, we investigated how the spatial selectivity of spatial filtering is affected by divided attention. Specifically, consider a dual task in which two stimuli are presented and the participant is instructed to judge them independently with two separate responses. Is spatial filtering less effective when both stimuli must be processed even though only one stimulus is relevant to each response? There are results in the literature that congruency effects increase for dual tasks compared to single tasks (e.g., Bonnel, Stein & Bertucci, 1992; Logan & Gordon, 2001). This is inconsistent with typical theories of spatial selectivity that assume local perceptual

Moreover, how do such dual tasks compare to when one stimulus is relevant and the other stimulus is entirely irrelevant (single tasks)?

processes are independent for widely separated stimuli. It is also inconsistent with typical theories of divided attention that pose limits on processing capacity and not selectivity. To address these unexpected results, we examine the properties of congruency effects for single and dual tasks. The results help discriminate between alternative theories of spatial selection and of divided attention.

Before proceeding, it is helpful to elaborate how spatial filtering is distinct from other paradigms used to study spatial selective attention and why it is the focus of the current study. First compare spatial filtering and partially-valid cueing (Posner, 1980). In spatial filtering, some stimuli are relevant (targets) and must be responded to because they appear in a cued location, whereas other stimuli are irrelevant (foils [redacted]) and must not be responded to because they appear in an uncued location. In partially-valid cueing, by contrast, there are no irrelevant stimuli. Instead, the probability of where a relevant stimulus is likely to occur is varied and cued. Given these differences, partially-valid cueing is useful for studying the differential allocation of attention among multiple spatial locations in which relevant stimuli can appear, whereas spatial filtering is useful for studying spatial selection of relevant stimuli to the exclusion of irrelevant stimuli. A direct comparison of these paradigms was conducted in Yigit-Elliott, Palmer and Moore (2011). Second, compare spatial filtering and the flanker paradigm (Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979). Again, in spatial filtering, a relevant stimulus is specified only by whether it is in a cued location or not, and therefore, the task depends on spatial selection. In the flanker paradigm, by contrast, the relevant stimulus is specified by multiple cues, designed to maximize the successful selection of the target stimulus regardless of the basis of selection, to the exclusion of irrelevant [redacted] stimuli. Cues in the flanker paradigm include spatial location, typically combined with foveal positioning, the relative position within a multiple stimulus array (typically the center), and sometimes other stimulus properties such as color (Harms & Bundesen, 1983). Given these differences, spatial filtering is useful for studying the properties of spatial selectivity which is the focus of the current study, whereas the flanker paradigm is useful for revealing processing interactions that occur despite excellent cues for selection (e.g., crosstalk, Navon & Miller, 1987). In summary, spatial filtering is specialized to reveal spatial selectivity between relevant and irrelevant stimuli.

Studies of Spatial Selectivity using the Spatial Filtering Paradigm

To quantify spatial selectivity, our lab has conducted several studies of spatial filtering using two disks in the periphery (see Palmer & Moore, 2009 for a review of other approaches). One peripheral location is cued as relevant and then two disks are briefly displayed with one at the relevant location and another at an irrelevant location with the same eccentricity. The observer must make a judgment about the relevant disk and ignore the irrelevant disk. In the most relevant of these studies for current purposes (Yigit-Elliott, 2012), each disk had a color that was chosen from one of two possible categories such as {"red", "green"} versus {"blue", "yellow"} and the task was to judge the color category of the relevant disk. The colors for the relevant and irrelevant disks were independent and thus half the time they were from the same category (*congruent*) and half the time from different categories (*incongruent*). If selectivity fails and the observer therefore bases their judgment on the stimulus in the uncued location instead of on the stimulus in the cued location, it will result in an error in the incongruent condition but not in the congruent condition. If selectively fails completely, then performance in the incongruent condition should be at chance (50% in this two-choice task), whereas if selectivity is perfect, performance should be equal in the congruent and incongruent conditions. Thus, congruency effects (i.e., differences in performance in congruent and incongruent conditions) in a spatial filtering paradigm provide a measure spatial selectivity.

The Yigit-Elliot (2012) filtering experiment was conducted with disks of 0.7° diameter at an 8° eccentricity and used two separations between the relevant and irrelevant disks. The separations were 1° and 11° degrees of visual angle which is equivalent to polar angles around fixation of 6° and 90°. In other words, the disks were almost touching in the small separation, and were 1/2 way around the display from one another in the large separation. For the small separation, accuracy was 98% for the congruent condition and 80% for the incongruent condition. The difference is a congruency effect of 18±2%. In contrast, for the large separation, accuracy was 99.0% for the congruent condition and 98.5% for the incongruent condition, a congruency effect of 0.5±0.1%. This result illustrates how congruency effects in spatial filtering are sensitive to separation. With small enough separations in this task, congruency effects should approach 50%. And the results of this experiment show that they fall to less than 1% with a large separation. To further quantify the selection process, we estimated the critical separation at which congruency effects were halfway between perfect and chance. In Palmer and Moore (2009), the critical separation was as small as 1° for stimuli that were 8° in the periphery. Similar results were found in Yigit-Elliott et al. (2011).

The congruency effects in these spatial filtering experiments can be accounted for by errors of selection. The locus of selection error, however, might be within early perceptual processing, such as with "imprecise targeting" as described by Bahcall & Kowler (1999), or alternatively, it might be within later processes, after immediate perceptual processing, such as with "selection by decision" as described by Palmer & Moore (2009). Elaborating the selection-by-decision hypothesis, imagine that two percepts are formed for the two disks. Each percept has a perceived location. These perceived locations are then compared to the representation of the cued location and the closest of these percepts is selected for further processing to determine the response. When stimuli are close together, limited localization results in a chance of selecting the irrelevant instead of the relevant stimulus for the required judgment. When stimuli have an increasing separation, the chance of selecting the irrelevant stimulus falls toward zero. This results in congruency effects that go from 50% (chance) to 0%. Insert 8A

We investigated the locus of errors in spatial filtering by adapting the simultaneous-sequential paradigm (Shiffrin & Garnder, 1972) to the spatial filtering paradigm, comparing performance with simultaneously presented relevant and irrelevant stimuli to performance with sequentially presented relevant and irrelevant stimuli (Moore & Palmer, 2016 [Psychonomics]). If errors in spatial filtering arise from having to process both relevant and irrelevant stimuli simultaneously within immediate processing such as is maintained by the imprecise-targeting hypothesis, then there should be an advantage for the sequential condition over the simultaneous condition. Alternatively, if errors arise within some later process, such as is maintained by the selection-by-decision hypothesis, then there should be no advantage for sequential presentation, and therefore performance is predicted to be the same in the simultaneous and sequential conditions. To clarify this latter prediction, consider that by hypothesis, the cued and uncued disks are perceived equally well, and there is therefore no advantage provided by sequential presentation. The error comes later in processing when deciding about the two percepts (e.g., which one is closer to the cued location), which is unaffected by sequential versus simultaneous presentation. Results from this experiment confirmed that performance was similar in the simultaneous and sequential conditions indicating that the locus of errors in this spatial filtering task derive from later process such as selection by decision.

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The premotor theory hypothesis differs in that the selection process occurs before the stimuli. Locations close to the cued location are selected for processing before the stimulus is presented. The stimulus closest to the selected location is fully processed and determines the response. Similar to selection by location, for close together stimuli, limited localization results in the chance of ~~processing~~ selecting the irrelevant rather than the relevant stimulus. This results in a similar large effect of separation on congruency.

To further pursue the nature of spatial selectivity, we investigated whether errors on incongruent trials in spatial filtering arise from a graded process such as attenuation of representations of stimuli in uncued locations at some level of processing (Treisman, 1960) or an all-or-none process such as the blocking representations of uncued items at some level of processing from accessing further processing (Broadbent, 1958). This was tested by varying the contrast of the relevant and irrelevant stimuli. A graded process like attenuation predicts that increasing the strength (i.e., the contrast) of an irrelevant stimulus can overcome its attenuation and therefore errors increase with increasing contrast of irrelevant stimuli. Alternatively, an all-or-none process like blocking cannot be overcome with increasing contrast of the irrelevant stimuli and therefore any the errors should asymptote with increasing contrast of the irrelevant stimulus. In three studies (Palmer & Moore, 2009; Yigit-Elliott, et al., 2011; Yigit-Elliott, 2012), there was clear evidence that errors in a spatial filtering task like those described here were due to an all-or-none process such as blocking and not to a graded process like attenuation.

The set of studies reviewed in this section sketches a story of how spatial filtering works. Errors in spatial selection occurred with a critical separation of about 1° (at 8° eccentricity), whereas spatial selection was almost perfect at large separations. The errors occurred within a process that is later than immediate perception, such as in decision. And, finally, the errors arose due to an all-or-none mechanism such as blocking, rather than a graded process such as attenuation. The experiments ruled out the possibility that the errors occurred within any process that depended on relevant and irrelevant stimuli being present simultaneously, such would be expected if they were due to crowding or a perceptual capacity limit.

A Failure of Spatial Selectivity

While spatial selectivity is good for the cases just reviewed, there are cases in which spatial selectivity is not as good. Specifically, there are studies showing that tasks requiring divided attention do not show good spatial selectivity even for widely separated stimuli. Consider a dual task that requires separate judgments of two widely separated stimuli. For each individual judgment, one of the stimuli is relevant and the other is irrelevant. Thus the individual judgments require spatial filtering. But because there are two judgments, both stimuli are relevant to the task as a whole. Consider as examples two studies that investigated such dual tasks.

The first example is Experiment 1 of Bonnel, et al. (1992). They compared performance for detecting luminance increments in single and dual tasks and measured both dual-task deficits and congruency effects. An observer viewed two continuously illuminated LEDs to either side (left and right) of fixation. On a trial, each of these LEDs independently incremented in luminance or remained constant. For each LED, observers indicated if an increment occurred by a yes-no response and confidence judgment. There were many conditions, but we focus on comparing the single-task condition when only one stimulus was relevant and the dual-task condition with instructions to "equally allocate attention". There was little or no difference in overall performance between the single and the dual tasks (no dual-task deficit). But what about congruency effects? For the single task, there was little or no congruency effect (77% versus 78% correct for congruent versus incongruent responses, see their Table 2). For the dual task, however, there was a 15% congruency effect (82% versus 67% correct for congruent versus incongruent responses). Thus, despite widely separated stimuli, there were congruency effects for the dual task that were larger than those found for the single task. In a further experiment, they showed that this difference in congruency effects for single and dual tasks was also obtained for discriminating between increments and decrements, which do have dual-task deficits. These two sets of results are surprising: the lack of dual-task deficit suggests that there is no processing capacity limit for detecting two light increments at once. Moreover, the lights were so far apart that their locations should not be confusable. So why are there such large congruency effects? That is the question we seek to understand here.

The second example is Experiment 1 of Logan and Gordon (2001). An observer viewed, displays of two digits: one above the other near fixation. The task was a magnitude judgment of each digit: press one key if the digit was less than "5" and another key if the digit was greater than "5" (the digit "5" was never shown). The digits were either presented simultaneously or sequentially but we focus on the simultaneous condition here. Observers were instructed to either make a single response to one of the digits (single-task condition), or to make two separate responses, one to each digit in turn (dual-task condition). In this experiment, the primary measure was response time. (Accuracy was high and nearly constant at 95% correct for both single and dual-task conditions.) There were several results. First, there was a dual-task deficit. The overall mean response time was faster for the single task than the first response of the dual task (~575 ms versus ~725 ms, respectively). What about congruency effects? For the single task, the congruency effect was near zero (~568 and 565 ms for congruent and incongruent conditions, respectively). For the dual task, the congruency effect was 60 ms for the first response (~695 ms versus 755 ms for congruent and incongruent, respectively), and the congruency effect was 146 ms for the second response (~890 ms versus 1036 ms for congruent and incongruent respectively). Thus, there was a substantial congruency effect for the dual task and little or no congruency effect for the single task. In further experiments, Logan and Gordon showed a similar pattern of congruency effects for judgments of color patches and color words, and for judgments of pictures and words.

We selected these two examples because they required spatial filtering for the component tasks. There are similar examples from dual-task versions of the flanker paradigm (Hubner & Lehle, 2007). A review of this larger context is deferred to the general discussion. To summarize, spatial filtering experiments that involve a single task show a high degree of spatial selectivity with little or no congruency effects for widely separated stimuli. In contrast, spatial filtering experiments that involve a dual task, show congruency effects even for widely separated stimuli.

We have been discussing the congruency effects in these studies as reflecting errors of selection. There is, however, an important alternative hypothesis to consider. Assuming parallel processing of the stimuli, there could be interactions, like crosstalk between information channels, that cause congruency effects separate from any failures of selection. Such *interactive processing hypotheses* have been proposed widely as explanations for congruency effects in both the flanker paradigm (Eriksen & Eriksen, 1974) and in dual tasks (Navon & Miller, 1987; Hommel, 1998). Interactive processing explanations have also been described for other related domains including crowding in perception (e.g., Parkes, Lund, Angelucci, Solomon & Morgan, 2001), memory interference (e.g., Oberauer & Lin, 2017) and response priming (e.g. Morton, 1969). Interactive processing accounts are tested in Experiment 1 and discussed in the General Discussion.

Goals

To maximize the effects of divided attention on the spatial selectivity of spatial filtering, we used conditions in which filtering is nearly perfect for a single-task condition. Specifically, separate detection tasks were used for two widely separated stimuli. To foreshadow the results, when only one stimulus is relevant (single-task condition), there were little or no congruency effects. But when both stimuli are relevant (dual-task condition), there were substantial congruency effects which indicates a failure of spatial selectivity.

We asked three questions about the increased congruency effects found for dual-task conditions that are analogous to those that we asked about errors in our earlier spatial filtering studies. First, are these dual-task congruency effects due to selection error (Yantis & Johnston, 1990), interactive processing (Navon & Miller, 1987), or both? Second, is the locus of these dual-task congruency effects in immediate processes (e.g., stimulus-driven perceptual processes), in later processes (e.g., decision), or both? Third, are these dual-task congruency effects due to errors in a graded process (e.g., attenuation, Treisman, 1960) or an all-or-none process (e.g., blocking, Broadbent, 1958)? Answering these questions distinguishes among ~~the~~ these possible theories of spatial filtering tasks. Insert 13A

General Methods

Overview

We investigated the detection of a simple visual pattern, a horizontal Gabor patch in visual noise: Is there a horizontal Gabor patch in noise or just noise? Target displays with Gabor patches and distractor displays with just noise were presented equally often and required a yes-no-like response in the form of a confidence rating. Our primary comparison was between a dual task and a single task condition. In the dual task, there were two relevant stimuli that were either congruent or incongruent. In the single task condition there was one relevant stimulus and one completely irrelevant stimulus that was either congruent or incongruent.

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~~[illegible]~~, These three questions identify 18 kinds of theory (3×3×2).

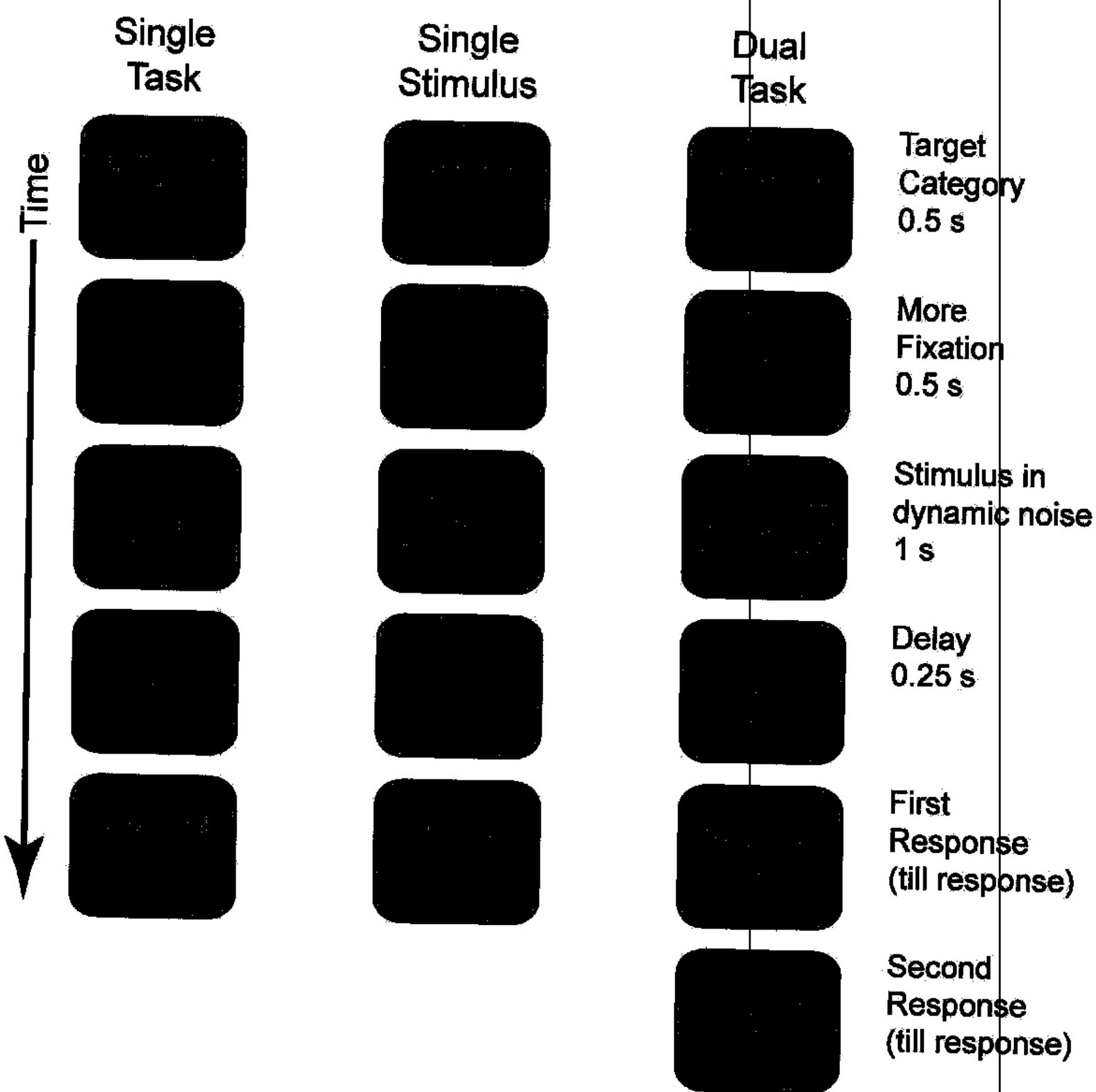

Figure 1. An illustration of the general procedure. The stimulus sequence is shown for the three main conditions: single task, single stimulus, and dual task. All conditions begin with a fixation display (along with a word reminding the subject to look for horizontally-oriented targets). After a brief delay, the stimuli are displayed within a 1 s movie of dynamic 1/f noise. Then after a delay, the observer is prompted for a response using a response prompt that specifies the relevant side of display for this response (the red line for some subjects, blue for others). In the single-task condition, the relevant side is blocked and the observer is informed at the beginning of the block. In the single-stimulus condition, everything is the same except that there is no stimulus or noise on the irrelevant side. In the dual-task condition, both sides are relevant for every trial of a block. The display sequence is identical to the single-task condition, but with both sides tested in sequence.

(With sin phase, the grating is at zero in the center of the patch. In contrast with cos phase, the grating peaks at the center of the patch.)

Stimuli

The stimuli were either a noise movie or a noise movie that included a brief presentation of a single horizontal Gabor patch. Observers judged the presence or absence of the Gabor patch. The Gabor patch was always horizontal with the grating component in sin phase and a spatial frequency of 1 c/d. The envelope component was a Gaussian with a standard deviation of 0.5°. It was truncated to a maximum size that was four times the Gaussian standard deviation (4 x 0.5° = 2°). The contrast of the Gabor patch was adjusted by the experimenter during practice to achieve overall performance around 75% to 85% correct for each observer. The resulting contrast values ranged from 18-35%.

The Gabor stimuli were presented briefly with temporal uncertainty during the relatively long dynamic noise display. Specifically, the Gabor contrast was modulated by a Gaussian temporal waveform that had its peak during the noise display and a standard deviation of 0.05 s. The peak was restricted to not occur in the first or last 0.2 s of the display. Consequently, the effective duration of this Gabor was about 0.1 s. This is much shorter than the noise display duration of 1.0 s. The onset of the target was the same for the two tasks to prevent the strategy of switching the attended side after seeing one target. This synchrony of target presentation was the only way in which the physical stimuli for the two tasks were dependent on one another.

Procedure

The procedure is illustrated in Figure 1 which shows the stimulus sequence for the three conditions of the first experiment. Consider first the *single-task condition* in the left column. A trial began with a fixation cross and a word by indicating the relevant target's orientation ("horizontal"). The target was always horizontal, but the label was included because this experiment was run alongside other experiments with semantic categorization of words that will be published separately. Observers were instructed to maintain fixation and it was enforced by monitoring eye position on all trials. After a brief interval, a display of dynamic noise was presented for 1 s. During that time, a Gabor patch might be presented with a duration of about 0.1 s (see Stimulus Section). There were noise displays on both sides for this condition, and the relevant stimulus was predictably on one side for a block of trials. Thus, the observer's task was to judge just one side (hence *single-task condition*). After a short interval to avoid masking, there was a post-cue that prompted to respond: one line ~~near~~ fixation ~~pointing to the right~~, and another to the right. Each observer was assigned a cue color (red or blue) and was to respond according to the stimulus on the side with the cued color. For the example illustrated in the figure, the relevant cue is blue. It is on the left and accordingly an observer is to respond to the stimulus on the left. This arbitrarily assigned color cue is used so that the displays have no purely visual differences between the left and right sides. For the single-task condition, this response prompt was always on the same side for the entire block. The trial ended with a response in the form of a confidence rating and tone feedback was given for errors.

Next consider the *dual-task condition* shown in the rightmost column. The displays were identical up to the response prompt. A block of the dual-task condition differed from a block of the single-task condition in having tests of both the left and the right side. In the first experiment, two responses were required, one after the other. In the other experiments, only the response to one side was required. The side that was prompted first was unpredictable to prevent the preparation of a response while the stimuli were presented. In sum, the single-task and dual-task conditions had identical displays but differed in that the observer must perform one perceptual task (e.g., left side detection) versus two perceptual tasks (e.g., separate detection judgments of the two sides).

The third *single-stimulus condition* is shown in the middle column of the figure. The task was the same as with the single-task condition: Judge an entire block of trials with the relevant displays on one predictable side. The distinctive feature was to remove the irrelevant display. This allows one to test if the presence of an irrelevant display has any effect on performance. This would reveal a failure of selective attention that can reduce performance.

Of particular interest was the effect of cueing between the two relevant stimuli.

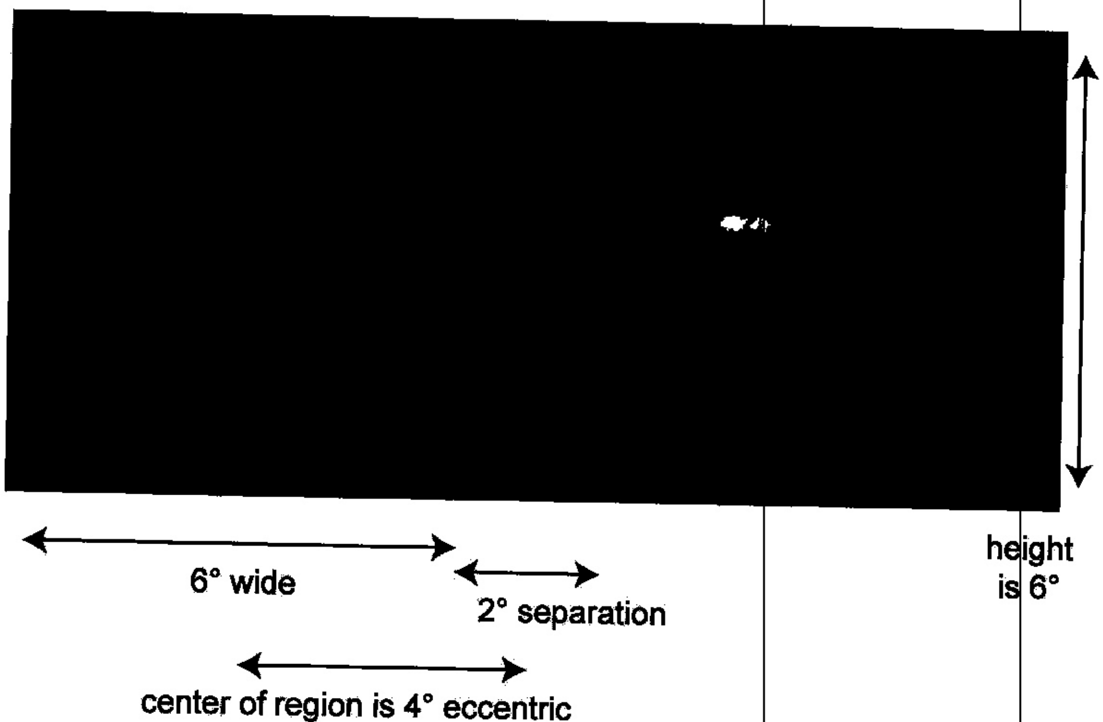

Figure 2. An illustration of a single frame of the stimulus display. Two examples of the 1/f noise are shown on each side of fixation. The display on the right includes a high contrast Gabor patch (80%). The figure also specifies the dimensions of each display element.

The spatial structure of the display is shown in Figure 2. The two noise movies were 6 by 6° to either side of a 0.5° fixation cross. They were each centered at an eccentricity of 4° which resulted in a 2° space between them. Overall, the two noise movies filled the middle 14° of a video monitor that had a viewable width of about 32°. An example Gabor patch is shown in the right side with a contrast of 80% which is much higher than used in all but the last experiment. It was presented with spatial and temporal uncertainty in the noise display. For example, the Gabor patch had a Gaussian envelope with a standard deviation of 0.5°. This made them effectively about 1° in size. The Gabors were excluded from near the edge of the display (< 0.5°) to prevent clipping the and the noise was attenuated to prevent sharp edges. As a result, the Gabors appeared anywhere in a region of 5 by 5° (25 square degrees).

The dynamic noise had spatial and temporal frequencies with amplitudes inversely proportional to frequency (1/f noise). Individual pixels had luminance values that were initially independently sampled from a Gaussian distribution and were then filtered in space and time so that each dimension had an amplitude at each frequency that was inversely proportional to the frequency. The luminance values of each pixel had a distribution with a mean at zero contrast and a standard deviation of 12% contrast. New noise frames were presented at a rate of 30 Hz (every 4th refresh of the 120 Hz display). In summary, the contrast for component frequencies varies inversely with the frequency. Thus, the noise has relatively more low frequency content than white noise. This kind of noise is useful because it equates the "power" per octave which is more relevant to human vision than equating the power per degree as in white noise (Field, 1987). Thus, 1/f noise is an effective [redacted] noise for stimuli with a wide range of spatial and temporal scales.

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The three main conditions (dual-task, single-task, single-stimulus) were blocked. In addition, the side for the single-task and single-stimulus conditions was blocked. This yielded 5 kinds of blocks: dual-task; left-single-task; right-single-task; left-single-stimulus; right-single-stimulus. To equate the number of trials in the primary conditions, there were 2 dual-task blocks along with 1 each of the 4 other kinds of blocks.

Analysis

Observers responded with one of four key presses that indicated likely-no, guess-no, guess-yes, or likely-yes. These ratings were used to form a receiver operating characteristic (ROC) function and performance was summarized by the percent area under the ROC (A_{ROC}). For reasonable assumptions, this A_{ROC} measure is equivalent to the percent correct measured by a forced choice paradigm (Green & Swets, 1966). To estimate A_{ROC} the simple trapezoid method was used to avoid making distributional assumptions (Macmillan & Creelman, 2005).

Each result ~~is~~ was described with several statistics: the standard error of the mean based on that sample alone, the results of the relevant hypothesis test, and 95% confidence intervals. Each hypothesis test was done as a planned contrast based upon a condition-by-subject, within-subject ANOVA. Our primary analysis was the congruency effects and the difference between congruency effects for dual and single tasks. We used one-tailed tests to gain sensitivity given that negative results were unexpected. For all secondary analysis, we used two-tailed tests.

Aspects of the Procedure Motivated by our Imaging Experiments

Two aspects of this procedure were intended to increase the size of a functional magnetic resonance imaging (fMRI) signal examined in a separate study (White, Runeson, Palmer, Ernst & Boynton, 2017). The spatial extent of the noise display was relatively large (6x6°) and nearly all of it is relevant to the judgment due to the spatial uncertainty of the target. The duration of

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The congruency effect was always between the left and right displays, whether they were both relevant (dual task) or only one was relevant (single task). Congruent displays could either have targets (horizontal Gabor patches) in both displays or noise alone in both displays. Incongruent displays had a target in one display and noise alone in the other display. The two targets were identical in orientation and contrast but varied in position and in the surrounding noise pattern.

the noise display was relatively long (1 s) and nearly all of it is relevant due to the temporal uncertainty of the target. In summary, the large and long noise displays provided a potent signal for our related fMRI study.

Observers

In each experiment there were 6 observers. Many were in multiple experiments and over the series of experiments there were a total of 11 observers. Some were unpaid volunteers and others were paid $20/hr. All had normal or corrected-to-normal vision. Each gave informed consent in accordance with the University of Washington Institutional Review Board in adherence with the Declaration of Helsinki.

To determine the appropriate sample size, we used data from two previous spatial filtering experiments that had measured congruency effects (Yigit-Elliot, et al., 2011, Experiment 1; Yigit-Elliot, 2012, Experiment 2.2). These studies varied contrast widely so performance varied from chance to perfect. From this range, conditions were selected that had similar performance levels as the current study (70-90% correct). In addition, the number of selected trials was similar to the current study (~300 congruent and ~300 incongruent trials). For the selected conditions from the two experiments, the standard deviation of the congruency effect was 2.62% and 4.96% for an average of 3.79%. Based on this variability, ~~discriminating~~ detecting a congruency effect of 5% with 80% power in a one-tailed t-test required a minimum sample of n=6. To further evaluate this choice, we did a post hoc analysis based on the current experiments. For Experiments 1, 2 and 3, the standard deviation of the congruency effects observed for both single- and dual-task conditions had a grand mean of 3.68%. Based on this standard deviation, ~~discriminating~~ detecting a congruency effect of 5% with 80% power in a one-tailed t-test also required a minimum sample size of n=6. Thus, the sample size was adequate to detect a congruency effect of 5%.

Display Apparatus and Eye Movement Monitoring

The stimuli were displayed on a flat-screen CRT monitor (19" ViewSonic PF790) controlled by a Power Mac G4 (Dual 1.0 GHz) using Mac OS X 10.6.8. The experiment was displayed at a resolution of 832 x 624 pixels, a viewing distance of 60 cm (25.5 pixel/degree at screen center), and a refresh rate of 120 Hz. The monitor had a peak luminance of 119 cd/m², and a black level of 4.1 cd/m², mostly due to room illumination. Stimuli were displayed using Psychophysics Toolbox 3.0.11 for Matlab R2012a (Brainard, 1997). A chin rest with an adjustable chair ensured a fixed distance to the display.

On all trials, eye position was recorded using an EyeLink II, 2.11 with 250 Hz sampling (SR Research, ON). The EyeLink II is a head-mounted binocular video system and was controlled by software using the EyeLink Developers Kit for the Mac 1.11.1 and the EyeLink Toolbox 3.0.11 (Cornelissen, Peters, & Palmer, 2002). The position of the right eye was recorded for all trials, and trials were included in the analysis only if fixation was confirmed. When fixation failed, five consecutive high frequency tones were sounded and the trial was aborted. The percentage of aborted trials for each observer in each experiment ranged from 0.5% to 4.4% with an overall mean including all experiments of 2.0 ± 0.2%. Thus the observers maintained fixation on almost all trials and none of the analyses included trials with blinks or saccades to the stimuli.

The Importance of Randomized Response Order

We have employed a refinement intended to help isolate the role of perception in divided attention effects. Specifically, response prompts on dual-task trials indicate which response to make, in an unpredictable order (left then right or right then left). Using such a response prompt prevents an unintended prioritization of one response over the other. For example, it can prevent effects due to preparing the first response while still perceiving the other stimulus. In a previous study (Ernst, et al., 2012), we found in pilot work that there was an order effect when the responses were in a fixed order but not when using an unpredictable order. Such fixed order cues might have contributed to finding dual-task deficits in some previous studies of simple detection tasks (e.g. Pastukhov, Fischer, Braun, 2009).

In addition, there is evidence from speeded dual tasks indicating the informativeness of using tasks in an unpredictable order (Lyphout-Spitz, Maquestiaux, Ruthruff, & Chaloyard, 2022).

Experiment 1

In this experiment, we measured the effect of divided attention on spatial selectivity. In addition, we began to distinguish between theories of selection error versus interactive processing as explanations for congruency effects.

Methods

In the first experiment, congruency effects and dual-task deficits were measured for detecting Gabor patches. As just described, there were 3 blocked conditions: single task, single stimulus, and dual task. In addition, the data from the dual-task condition were broken down by the first or second response. There were 6 observers who, after practice, participated for 5 hours resulting in 640 trials in each of the 4 main conditions for each observer.

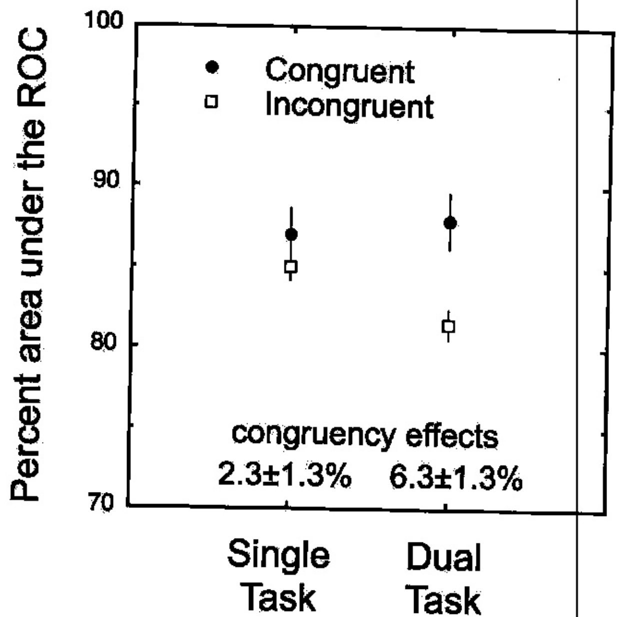

Figure 3. Results of Experiment 1. The percent area under the ROC is plotted for the single-task and dual-task conditions. This measure can be thought of as an unbiased percent correct. These conditions are further broken down by whether the trial had congruent (solid disk) or incongruent (open square) stimuli. The congruency effect (difference between congruent and incongruent) was larger for the dual-task condition compared to the single-task condition.

(Green & Swets, 1966)

Results

Congruency effects. For all of the results, performance was measured in terms of the percent area under the ROC function. As described in the methods, this measure can be thought of as an estimate of the unbiased percent correct. Our primary interest are the congruency effects. The stimuli in the two tasks are congruent if they require the same response. The effect of congruency is shown in Figure 3 for the single-task and the dual-task conditions. These conditions are broken down by whether the trial had congruent (solid disk) or incongruent (open square) stimuli. The statistical analyses are planned contrasts for the congruency effects using a common error term based on a condition-by-subject, within-subject ANOVA ($F(3,15) = 9.30$, $p = .001$). For the single task, the congruency effect was relatively small and not ~~only marginally~~ significant ($2.3 \pm 1.3\%$, 95% CI -0.5, 5.2%, $t(15)=1.74$, $p=.051$, one tailed). In contrast, the dual-task congruency effect was larger and significant $6.3 \pm 1.3\%$ (95% CI 3.5, 9.2%, $t(15)=4.72$, $p<.001$ one tailed). The difference between the congruency effects in the dual and single tasks was also significant (4.0 ± 1.9, 95% CI -0.04, 8.0% $t(15)=2.11$, $p=.026$, one tailed). Thus, congruency effects were larger for the dual-task condition than the single-task condition. A further analysis of the ROC underlying the area measure is presented in Appendix A. It provides additional evidence that the congruency effect is due to changes in sensitivity and not bias.

Dual-task deficits. To give the most sensitive measure of dual-task deficits, we combined the single task and single stimulus conditions and the two responses in the dual-task condition. The difference between aggregated single-task and dual-task conditions was $1.4\pm0.7\%$ which was not significant (95% CI -0.4, 3.2%, $t(5)=1.97$, $p=.106$, two tailed). This dual-task deficit is small compared to the dual-task deficit found for other stimuli under similar conditions (e.g. up to 15% effects with masked words, White, Palmer & Boynton, 2018; 2020). Thus, there was little dual-task deficit for Gabor detection. This was expected based on prior studies of dual-tasks using detection judgments (e.g., Bonnel, et al., 1992; White et al. 2017).

Secondary effects. We also describe three secondary effects to provide context. First, the difference between the single-task and single-stimulus conditions was near zero (0.1±1.0%, 95% CI -2.4, 2.5%, $t(5)= 0.09$, $p>.1$, two tailed). This is consistent with near perfect selection and no interference between stimuli in the single-task condition, as expected with a large separation between stimuli. Second, the difference between the first and second responses for the dual-task condition was also near zero, and is not significant (-0.7±0.5%, 95% CI -2.0, 0.5%, $t(5)=1.47$, $p>.1$, two tailed). This is consistent with no memory or response interference that was worse for the second response compared to the first. Third, we measured the correlation between the two responses on a single trial. Parallel and serial models make different predictions about such correlations (Sperling & Melchner, 1978). Typical serial models predict negative correlations between a correct response on one task and a correct response on the other task. Typical parallel models in themselves predict no correlation. But, any common noise source for the two tasks would introduce a positive correlation. In this experiment, there was a small but significantly positive correlation of .046 ± .015, (95% CI .007, .085, $t(5)= 3.01$, $p=.030$, two tailed). One can also consider the correlation broken down by the kind of trial. For target-target trials it was .05±.03. For target-distractor trials, it was -.01±.01. And for distractor-distractor trials, it was .18±.07. Thus, trials with two distractors and no targets had the largest positive correlation. This pattern of correlations was also found for the color tasks in White et al. (2018). In summary, there was no sign of the negative correlation expected from a serial model. For dual-task experiments that find such negative correlations, see Sperling and Melcher (1978) or White, et al. (2018; 2020).

Discussion

The primary result of this experiment was the larger congruency effect for the dual-task condition relative to the single-task condition. This confirms the occurrence of congruency effects specific to conditions with divided attention that were previously reported by Bonnel et al. (1992) and Logan and Gordon (2001).

Consider the possible interpretations of congruency effects being larger for the dual-task condition. In this experiment, the single-task and dual-task blocks differed only in the knowledge of which stimulus would be post-cued. Because the stimuli were identical, any stimulus-driven process must also be identical. Thus, any interactive processing that is a function of the stimuli and not top-down control does not predict the congruency effect being specific to the dual-task condition. In contrast, the results are consistent with the either errors in selection or an account that combines selection and interactive processing. We consider further these two possibilities in the General Discussion. In summary, the use of identical displays in both the single- and dual-task conditions allows us to reject a pure, stimulus-driven interactive processing account of the congruency effects.

Experiment 2

In this experiment, we tested whether the congruency effects found with Gabor detection were due to immediate processing such as perception or memory encoding; or, were due to later processing such as memory or decision processing that is not tied to the presence of the stimulus. The approach was to compare a simultaneous display of two stimuli to sequential displays in which the stimuli were displayed one after the other. In the visual search literature, this comparison has been used to test if the dependency between the stimuli is specific to immediate processing (Shiffrin & Gardner, 1972; Scharff, et al., 2011a, b). The strategy has been used less often with dual tasks (but see Duncan, 1980). Most relevant to the current experiment is the comparison of simultaneous and sequential presentations in Logan and Gordon (2001).

Methods

Experiment 2 combined the dual-task and single-task conditions from Experiment 1 with two new conditions as shown in Figure 4. The four conditions are in separate columns. The leftmost column is the single-task condition which is unchanged from Experiment 1. Recall the relevant side was cued for an entire block. The second column is the simultaneous dual-task condition. This was also unchanged except for measuring only one of the two possible responses.

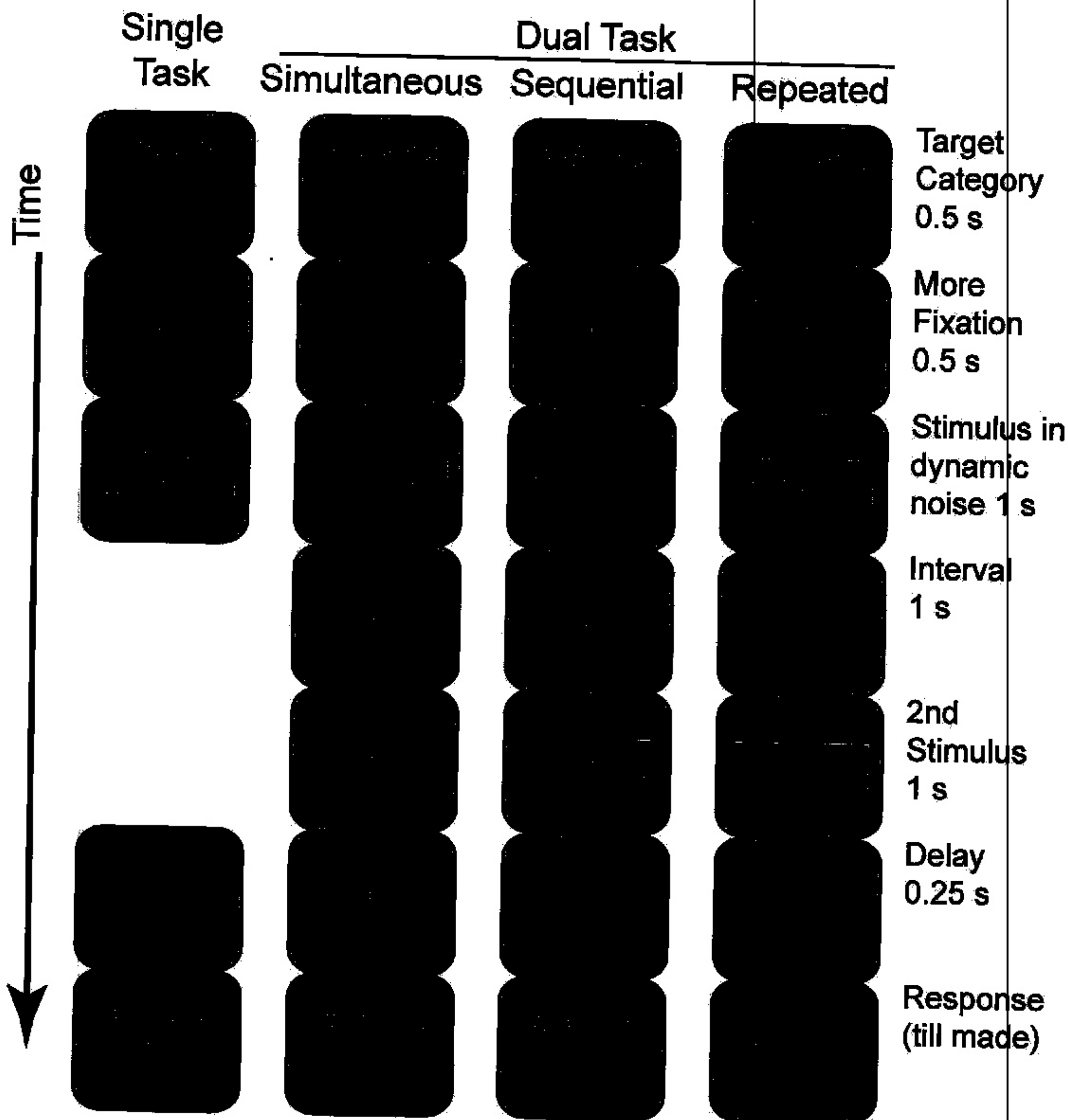

Figure 4. Illustration of the procedure of Experiment 2. The stimulus sequence is shown for the four conditions: single task, simultaneous dual task, sequential dual task, and repeated dual task. All conditions have the same initial and ending displays as the previous experiments. The single-task and simultaneous dual-task conditions are the same as the previous experiments. In the sequential-dual-task condition, the stimuli for the left and right sides are presented in separate displays with an intervening interval of 1 s. In the repeated-dual-task condition, the display for the simultaneous dual-task condition is repeated in a second display.

The third condition is the *sequential dual task*. The new feature was that the critical stimulus display is split into a pair of displays shown in sequence. In this example, the left-side stimulus was shown first and the right-side stimulus was shown second. This order of left or right displays was blocked. The duration of the individual displays was unchanged (1 s). The interval from the end of the first display to the beginning of the second display was 1 s. Such a long interval is likely to provide sufficient time to shift attention from side to side (e.g., Ward, Duncan & Shapiro, 1996). The logic of adding this condition is that if the dependency between the tasks is specific to immediate processing, then it should disappear for this sequential condition. One can think of this sequential condition as being equivalent to a sequence of single-task conditions. On the other hand, if the dependency in not due to the processing of the immediate stimulus, then performance should be unchanged between the simultaneous and sequential conditions.

The fourth condition is the *repeated dual task*. It also had two sequential displays. But these displays repeat the entire simultaneous display rather than split them apart. This purpose of adding this condition is to provide a comparison for the expected size of the dual-task deficit. For a class of fixed-capacity models, the difference in performance between dual and single tasks (dual-task deficit) is predicted to match the difference between the repeated and simultaneous dual-task condition (Scharff, et al., 2011a; 2013). To get an intuition, assume a serial model that can process only a single stimulus in the brief displays of this experiment. Then the dual-task deficit arises because in the dual-task condition only one of the two stimuli can be processed while in the single-task condition it is sufficient to process the one relevant stimulus. Similarly, the repeated effect arises because only one of the two stimuli can be processed in the simultaneous dual-task condition while both of the stimuli are processed in the repeated dual-task condition. In other words, the repeated condition gives an observer a second chance at the second stimuli which makes it as good as the single-task condition.

In summary, this experiment combined the dual-task paradigm with a comparison of simultaneous and sequential displays. There were 4 main conditions: single task, simultaneous dual task, sequential dual task and repeated dual task. There were six observers who, after practice, participated for 7 hours resulting in 672 trials in each of the 4 main conditions for each observer.

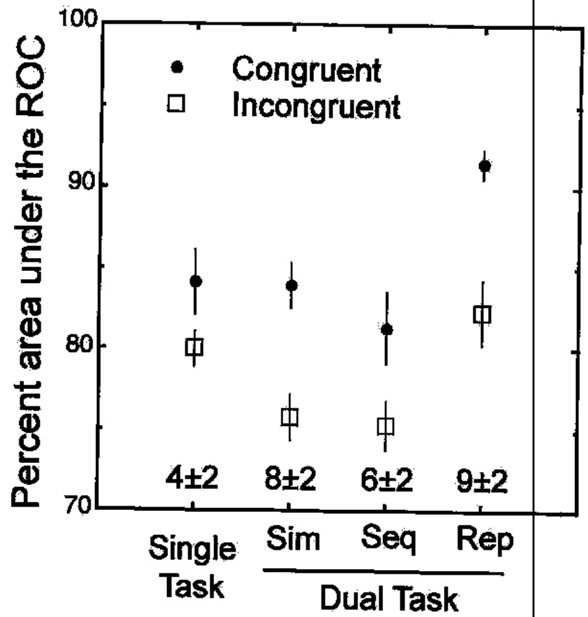

Figure 5. Results of Experiment 2. The percent area under the ROC is plotted for four conditions: single task, simultaneous dual task (sim), sequential dual task (seq), and repeated dual task (rep). These conditions are further broken down by whether the trial had congruent (sold disks) or incongruent (open squares) stimuli. There were significant congruency effects for all conditions.

Results

Congruency effects. In Figure 5, the four conditions are broken down by congruency and the values of each congruency effect are given at the bottom of the figure. As before, we used planned contrasts based on the error term for a condition-by-subject, within-subject ANOVA ($F(7,35)=21.00$, $p<.001$). There were significant congruency effects in all conditions: the single-task congruency effect was 3.8±1.6%, (95% CI 0.6, 7.1%, $t(35)= 2.39$, $p=.011$, one tailed); the simultaneous congruency effect was 8.5±1.6%, (95% CI 5.3, 11.7%, $t(35)= 5.32$, $p<.001$, one tailed); the sequential congruency effect was 6.1±1.6%, (95% CI 2.8, 9.3%, $t(35)= 3.79$, $p<.001$, one tailed); and the repeated congruency effect was 9.0±1.6%, (95% CI 5.8, 12.2%, $t(5)= 5.64$, $p<.001$, one tailed). The single-task effect was smaller than the other effects. For example, it was half of the effect for the simultaneous dual task (3.8 vs. 8.5) and this difference was significant (4.7±2.3, 95% CI 0.1, 9.3%, $t(35)= 2.07$, $p=.023$, one tailed). Recall the congruency effects in Experiment 1 with similar stimuli were 8% for the dual-task condition and 2% for the single-task condition. Combining over both experiments there were 4 dual-task conditions that on average had a congruency effect of about 8% and two single-task conditions that on average had a congruency effect of about 3%. Thus, for both experiments there is a larger congruency effect for dual tasks relative to single tasks.

The focus of this experiment is the sequential dual-task condition. For three of the four conditions, the stimuli were presented simultaneously. The sequential condition was different. Now the stimuli were presented sequentially with a full second between displays. If the congruency effect depends on immediate processing, then it should be absent in the sequential condition. In fact, there was a significant 6.1±1.6% congruency effect in the sequential condition. This result is consistent with the congruency effect being mediated by memory or decision rather than immediate processing such as perceptual processes. Insert 34A

Secondary effects. Overall performance in the four conditions was 82.1±1.4%, 79.9±1.2%, 78.3±1.3% and 87.1±1.3% for the single, simultaneous, sequential, and repeated conditions respectively. In words, performance was similar for the single, simultaneous, and sequential conditions and better in the repeated condition. Consider the two most relevant paired comparisons: the dual-task deficit (single-vs.-simultaneous) was 2.3±0.5%, which is significant (95% CI 1.1, 3.5% $t(5)= 5.00$, $p=.004$, two tailed); and, the sequential effect (sequential-vs.-simultaneous) was -1.6±0.8%, which is not significant (95% CI -3.6, 0.4%, $t(5)= 2.02$, $p=.099$, two tailed); Thus, there were small dual-task deficits and sequential effects that go in opposite directions. By comparison, in Experiment 1 the dual-task deficit was 1.4 ± 0.7% and not significant. An additional experiment described shortly also shows the dual-task deficit to be about 2%. Thus, the experiments in this article are consistent with a dual-task deficit of about 2% for Gabor detection. This is small relative to the 7% repeated effect, and the 8% dual-task deficit predicted by the fixed-capacity, parallel model for this performance level (Scharff, et al., 2011). We argue that the dual-task deficit is probably not completely absent for Gabor detection, but it is small relative to these other standards. In contrast, performance was reliably better for repeated dual task. The repeated effect (repeated-vs.-simultaneous) was 7.2±0.5%, (95% CI 6.0, 8.4%, $t(5)= 15.47$, $p<.001$, two tailed). This effect confirms that an additional display can improve performance. Thus, there is no ceiling on performance that is limiting the dual-task deficit.

Discussion

The primary result of Experiment 2 was that dual-task congruency effects occur for sequential conditions as well as simultaneous conditions. It replicates similar results found in

34A

If ~~[illegible]~~ both immediate and later processes contribute to the congruency effect, then in the sequential condition the congruency effect should be smaller than the ~~[illegible]~~ congruency effect in the ~~[illegible]~~ simultaneous condition. This difference was not significant ($2.5 \pm 2.3\%$, 95 CI $-2.1, 7.0\%$, $t(35) = 1.08$, $p = .29$, two tailed). Thus, the congruency effects differ in the direction consistent with both immediate and later loci, but the difference is not significant.

Logan and Gordon (2001) for quite different tasks. This result is consistent with the locus of the congruency effect being in later processes rather than immediate processes. If the locus had been in immediate processes, then there should have been no congruency effect in the sequential condition. Furthermore, if the locus was in both immediate and later processes, then most models predict larger effects in the simultaneous condition relative to the sequential condition. ~~This did not occur.~~ There was a hint of such a difference but it was not significant.

Experiment 3

In this experiment, we made three changes to the procedure in order to minimize sources of confusion that ~~could~~ might cause the congruency effects. Specifically, we made it easier for the subjects to respond to the two stimuli independently in the dual-task condition – most importantly, by having two separate sets of response keys. The question is whether the congruency effects persist.

Methods

This experiment had two conditions: a single-task condition and a dual-task condition with just one response. The details were the same as Experiment 1 with the following modifications:

1. Separate keys were used for the two sides. Using a separate small keypad, the four keys on the left edge were assigned to the left-side task and the four keys of the right edge were assigned to the right-side task. For both tasks, the relevant four keys were arranged vertically and from bottom to top referred to the same confidence levels as in Experiment 1: likely-no, guess-no, guess-yes, likely-yes. This arrangement minimized Simon effects and eliminated decision errors in which one attempted to respond to one side when prompted to the other.

2. Observers were instructed to emphasize accuracy and take their time. To encourage that, the prompt following the stimulus display was delayed for 1 s instead of the 0.25 s in previous experiments.

3. The nature of independence between the two responses was discussed with each observer. Specifically, the two-by-two contingency table of possible stimuli for each task was explained and it was emphasized that they should make the two decisions independent of one another.

There were six observers who, after practice, participated for 7 hours resulting in 1344 trials in each of the 2 main conditions for each observer.

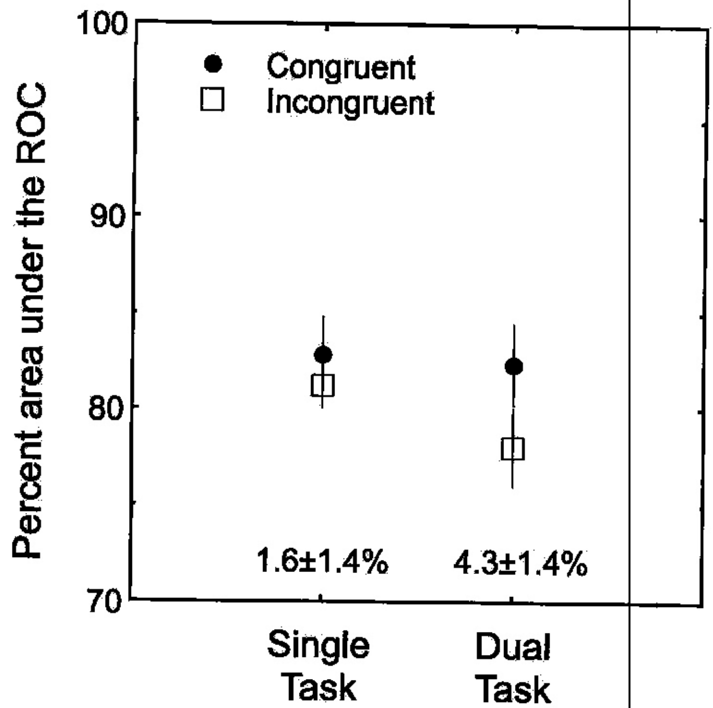

Figure 6. The congruency effects of Experiment 3. Percent area under the ROC is plotted for single-task and dual-task conditions. The congruency effects were larger for the dual tasks than the single tasks.

Results and Discussion

The effect of congruency is shown in Figure 6 for the two main conditions with the values of each congruency effect given at the bottom of the figure. The following planned contrasts were based on the error term from a condition-by-subject, within-subject ANOVA ($F(3,15)=4.61, p=.018$). For the single-task condition, the congruency effect was 1.6 ± 1.4% which is not significant (95% CI -1.5, 4.6%, $t(15)=1.11, p=.143$, one tailed). For the dual-task condition, the congruency effect was a significant 4.3 ± 1.4% (95% CI 1.3, 7.4%, $t(15)=3.03$, $p<.004$, one tailed). The congruency effect for the dual task was marginally larger than for the single task (2.8±2.0%, 95% CI -1.6, 7.1%, $t(15)=1.36, p<.097$, one tailed). Thus, the pattern of congruency effects was similar to the prior experiments: a robust congruency effect for the dual-task condition and a smaller effect for the single-task condition. In addition, the dual-task deficit was 1.8 ± 0.8% which was marginally significant (95% CI -0.3, 4.0%, $t(5)=2.19, p=.080$, two tailed). This is a similar small effect as found in the prior two experiments. Thus, the congruency effect is still strong even when subjects can respond to the two stimuli with separate hands, and are fully informed and encouraged to judge the two stimuli independently.

Experiment 4

Next, we turn to distinguishing between accounts of congruency effects that depend upon either all-or-none or graded processes. This was done by examining congruency effects at high contrast which can be compared to the congruency effects at low contrast of the prior experiments (similar to Palmer & Moore, 2009). For a single stimulus, detection of high contrast stimuli is expected to approach perfect performance. But with multiple stimuli, the expected performance depends on one's theory of congruency effects. Models with graded processes such as attenuation predict congruency effects to disappear at high contrast (this case is described [redacted] by the weighting model in Appendix B). In contrast, models with all-or-none processes such as blocking predict congruency effects to persist even at high contrast (this case is described [redacted] by the substitution model [redacted] in Appendix B). Furthermore, previous experiments with spatial filtering limited by small separations have shown that congruency effects persist at high performance levels. This result is consistent with all-or-none models. These predictions were pursued in this experiment for the Gabor detection tasks with widely separated stimuli.

Methods

This experiment included single-task and dual-task conditions for Gabor detection. The new feature was to use stimuli with 80% contrast rather than the 18-35% contrast used in the prior experiments. Otherwise, the details of the experiment follow those of Experiment 3 (e.g. separate keys for the left and right tasks). There were six observers who participated for 4 hours resulting in 192 trials in each of the main conditions. All had previous experience in at least one of the other experiments.

Results

The percent area under the ROC was 99.7±0.2% in the single-task condition and was 99.6±0.4% in the dual-task condition. Congruency effects were very small and not significant. For single tasks, they were -0.5±0.4% and for dual tasks they were 0.5±0.4%. Such a near zero congruency effect is consistent with typical graded models and not consistent with typical all-or-none models (see Appendix B). The dual-task deficit was 0.2±0.2% and not significant. In fact, four of the six observers were perfect on all trials of both conditions.

Discussion

In this experiment, we measured congruency effects for detecting a high contrast Gabor patch. In both single-task and dual-task conditions, performance was essentially perfect and there were little or no congruency effects. For a weighting model, congruency effects are predicted to decline as performance approaches perfection. In contrast, for a substitution model, performance in the incongruent condition can never be perfect and the congruency effect grows with contrast. Thus, these results were consistent with the weighting model (graded) and not the substitution model (all-or-none). These results stand in contrast to those in spatial filtering experiments with small separations (Palmer & Moore, 2009; Yigit-Elliott, et al., 2011). In those experiments, the congruency effects remained, even for clearly visible stimuli with perfect performance in the congruent condition.

General Discussion

Summary of Main Results

Despite using widely separated stimuli, three experiments revealed congruency effects in dual-task conditions. Furthermore, the experiments provide initial answers to the three questions regarding the source of these congruency effects that were raised in the introduction. First, all congruency effects were larger under dual-task conditions (6.4% average, Experiments 1 - 3) than under single-task conditions (2.5% average, Experiments 1 - 3). Because the stimuli were identical across single- and dual-task conditions, this indicates ~~a~~ some role for selection rather than an effect due to pure, stimulus-driven, interactive processing. Second, the congruency effect for dual tasks persisted even when the stimuli were presented sequentially (Experiment 2). This is consistent with the locus of the effect being in later processes rather than immediate processes. Third, the congruency effect for dual tasks disappeared for high contrast stimuli (Experiment 4). This is consistent with models that depend on graded processes rather than all-or-none processes. To illustrate this distinction, Appendix B provides formal examples of a graded process (weighting model) and an all-or-none process (substitution model).

Generality of Results

The current three experiments, which used widely separated stimuli, show congruency effects that are larger for dual tasks than single task. How general is this result? Our lab has conducted similar dual-task studies for a variety of tasks and stimuli. The results have been of several sorts. There was a similar pattern of differential congruency effects for 4 experiments on judgments of masked words (average congruency effects of 6% for dual tasks and 3% for single tasks, White, et al., 2018; 2020). In addition, there have been studies with smaller effects. A pair of experiments with masked objects (rather than words) showed smaller congruency effects (average congruency effects of 2% for dual tasks and 2% for single tasks, Popovkina, Palmer & Boynton, 2020). Smaller effects were also found for 3 word-categorization tasks in noise rather than with masks (average congruency effects of 2% for dual tasks and 2% for single tasks, Palmer, White, Moore & Boynton, 2020). There also have been an exception to these two patterns. For a masked color discrimination task there were substantial congruency effects for both single and dual tasks (average congruency effects of 6% for dual tasks and 6% for single tasks, White, et al., 2020). In summary, we mostly find two patterns for congruency effects in accuracy dual tasks:

(a) Differential effects. Found for detection tasks and for some masked tasks.

(b) Small effects. Found for object tasks and word tasks without masks.

There are hints in the literature for why the results for detection and masking tasks might differ from other tasks. A special role for detection task has been suggested by Bacon and Egeth

(1994) in their idea of a singleton detection strategy. One might gain sensitivity for detection by minimizing selectivity. By reducing selectivity, one becomes more subject to congruency effects. In addition, a special role for masking has been suggested by Morgan, Word and Castet (1998). In a visual search paradigm, they found that masking increased effects of divided attention and decreased the effectiveness of spatial selectivity. Again, decreasing selectivity is consistent with increasing congruency effects. To conclude, the pattern of congruency effects varies with the details of the task and stimuli.

Relation to the Flanker Paradigm

This article is focused on the observation of larger congruency effects in dual tasks compared to single tasks in the spatial filtering paradigm which, as elaborated in the introduction, is well-suited for isolating spatial selection processes. Similar findings have been reported from studies using the flanker paradigm, which involves selection processes beyond purely spatial selection.

Hubner and Lehle (2007) conducted several experiments combining the flanker paradigm with a speeded dual task. A target digit was presented at fixation with two flanker digits to either side. These flankers were always identical to one another and were displayed until the response(s) were made. The required judgment was to indicate the parity (odd versus even) of the target using one of two keypresses. For example, a congruent case would be a "4" target surrounded by two "6" flankers; and, an incongruent case would be a "4" target surrounded by two "7" flankers. The innovation was to add a dual-task condition with a second parity judgment of the flankers. The second judgment was made using a different hand and always followed the first response. They also varied the onset of the flankers from being simultaneous with the target to following the target by several hundred milliseconds.

Thus, these speeded dual-task conditions had the typical features of the psychological refractory paradigm (cf. Pashler, 1994).

There were several experiments establishing the generality of their results, but here we focus on Experiment 1 and on the conditions with simultaneous targets and flankers. First consider the response to the targets. For blocks of the single-task condition, the flanker effect was 20 ms (~475 versus ~495 for congruent and incongruent, respectively). For blocks of the dual-task condition the flanker effect was 180 ms (~760 versus ~940 ms). Regarding accuracy, over all conditions there were a mean of 3% errors and no effect on errors was found for manipulations of congruency or of single-versus-dual-task. Thus, the congruency effect on response time was almost an order of magnitude larger for the dual task than the single task. This result was replicated and generalized in multiple experiments in this paper and in a following paper (Lehle & Hubner, 2009). In particular, they showed how these effects were subject to strategy. For example, the larger congruency effect with dual tasks was reduced by mixing the single and dual-task trials but it did not go away. There is little doubt that congruency effects in the flanker task are increased in the context of a dual task. Further studies of flanker effects in the dual-task context (but without the single task comparison) can be found in Rieger and Miller (2020). In summary, the increase in congruency effects with a dual task appears to be general to both spatial filtering, which reflects purely spatial selection, and flanker paradigms, which reflect other forms of selection and interactive processing.

Interpretation of Results

As discussed above, the fact that identical stimuli and tasks were used in the single- and dual-task conditions of the current experiments, rules out a purely interactive process account of congruency effects, and implicates a role for errors in the selection process. A pure selection account, however, also has problems accounting for the larger body of evidence. A pure selection account for the current experiments would require a graded selection process like a contrast gain mechanism. Such selection processes have been ruled out in previous spatial filtering experiments that used a task very similar to that of the current study but with small separations (e.g., Yigit-Elliot, et al., 2011). Those experiments showed results consistent with all-or-none selection. Given the similarity of the experiments, it would be ad hoc to propose that selection is all-or-none for some filtering experiments and graded for others.

Our working hypothesis is that both selection and interactive processes contribute to congruency effects in the current experiments. Specifically, we propose a *two-process hypothesis* according to which selection is all-or-none (as in Palmer & Moore, 2009) but when one must maintain multiple stimulus representations, as under dual-task conditions, there is also a graded interactive process. For the dual-task condition, representations for both stimuli must be maintained and are subject to interactive processes in memory (Oberauer & Lin, 2017), or decision (Hommel, 1998; Logan & Gordon, 2001), giving rise to congruency effects. For example, there might be two noisy representations of the evidence for a Gabor on each side that are subject to crosstalk in memory. Final selection between these representations only occurs at the time of deciding each response. For the single-task condition, however, only one stimulus is relevant to the task. In this case, one can use an immediate all-or-none selection process so that only the representation of the relevant stimulus is passed to memory and other later processes. In the single task, selection protects the relevant representation from interaction with the irrelevant representation, but for the dual-task condition, both stimuli need to be processed in memory and therefore are impacted by interactive processing.

The two-process hypothesis has two positive properties. First, it is parsimonious in that only a single all-or-none selection process is proposed. Second, it maintains the understanding of interactive processes as being automatic (i.e., non-selective) that is typical of such accounts (e.g., Eriksen & Schulz, 1979; Hommel, 1998; Navon & Miller, 1987; Oberauer & Lin, 2017).

Alternative Theories

Perhaps the most relevant alternative theory to our two-process hypothesis is an account of congruency effects that was proposed by Logan and Gordon (2001). This study is particularly relevant because it used spatial filtering rather than the flanker paradigm. They also propose that congruency effects derive from a graded interactive process (crosstalk) within a late process. However, they propose that the difference in the size of congruency effects in dual- versus single-task conditions derives from a top-down control mechanism (the β parameter in their formal model) that modulates the degree of crosstalk. In the terms that we have been using, their model includes a graded selection mechanism that is more selective with single tasks than dual tasks. An advantage of the two-process hypothesis that we have proposed is that all-or-none selection accounts not only for the difference in congruency effects in dual- versus single-task conditions, but also the evidence of all-or-none selection with small separations (Palmer & Moore, 2009; Yigit-Elliot et al., 2011; Yigit-Elliot, 2012). In addition, the Logan and Gordon account makes cross-talk subject to top-down control, rather than being stimulus driven.

Another alternative theory has been described by Hubner and colleagues across several papers (Hubner, Steinhauser, & Lehle, 2010; Lehle & Hubner, 2009). It was developed in context of a flanker task that was generalized to include elements of the PRP paradigm. The theory has both an early selection mechanism, which is subject to inputs from irrelevant stimuli, and a later selection mechanism that is not (Hubner et al., 2010). In addition, as presented in the appendix of Lehle and Hubner (2009) it includes a version of central capacity theory (Tombu & Jolicoeur, 2003) that assumes crosstalk between processes for dual tasks consumes part of central capacity, thereby providing an account for larger congruency effects in dual-task conditions relative to a single task. Again, an advantage of the two-process hypothesis that we have proposed is that the all-or-none selection process accounts for both the difference in congruency effects in dual- versus single-task conditions and all-or-none selection with small separations (Palmer & Moore, 2009; Yigit-Elliot et al., 2011; Yigit-Elliot, 2012). In addition, a challenge of the Hubner and colleagues theory is explaining how the capacity limits cause a differential effect between congruent and incongruent stimuli.

In summary, our two-process hypothesis and the two theories just reviewed, all have different domains and different strengths. We focus on how each theory accounts for the difference in congruency effects for single and dual tasks. Logan and Gordon (2001) do this directly by modulating a graded selection process. Huber and colleagues do it by adding an additional claim to central capacity. Our working hypothesis does it as a side effect of an all-or-none selection process. While we think our working hypothesis is the simplest, it will take integrative studies combining the relevant phenomena to fully discriminate these possibilities.

Dual-task Deficits

The first three experiments in the current study all found small, barely detectable dual-task deficits of around 2%. Such small deficits are consistent with the previous experiments of Bonnel et al. (1992) and Graham et al. (1985). They contradict the claims of some studies (e.g., Lee, Koch & Braun, 1999; Pastukhov, Fischer & Braun, 2009) that all tasks have similar effects of divided attention. One reason for the apparent differences between studies might be the use of a fixed order of responses versus an unpredictable order of responses. With a fixed order, one

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must be resolved by
cognitive control processes that

can start to prepare for the first response rather than maintaining both decisions. This will make different tasks more homogeneous. We suggest that using an unpredictable order provides better insight into the diverse effects of divided attention.

Conclusion

Using widely separated stimuli in a spatial filtering paradigm, we found effects of congruency under dual-task conditions, but relatively little for single-task conditions. Because stimuli were identical in single and dual-task conditions, this indicates that spatial selectivity was reduced for dual tasks, rather than the difference being due a pure stimulus-driven interactive process. In addition, the dual-task congruency effect persisted with sequential stimulus presentation indicating that the locus of the effect is in a later process (e.g., decision), rather than an early immediate process (e.g., perception). Finally, the dual-task congruency effect disappeared with high-contrast stimuli, indicating that the effect was due to some kind of graded process rather than to an all-or-none process. Our working hypothesis is that there is an all-or-none selection process, which can also account for previous results with close stimulus separations (Palmer & Moore, 2009; Yigit-Elliot et al., 2011; Yigit-Elliot, 2012) and an interactive process that is graded in nature and occurs late in processing. The all-or-none selection can protect against interactive processing in a single task but not in a dual task when representations of both stimuli must be held in memory.

Author Notes

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Appendix A

Analysis of the Rating Data

In the body of this article, we summarized performance by A_{ROC}: the area under the ROC curve. As discussed in methods, this measure is an estimate of the unbiased proportion correct. In this appendix, the rating data is described from which A_{ROC} is estimated, and the congruency effects are broken down by targets versus distractors.

Rating data such as used here can be summarized by an ROC graph that plots the percent hits against the percent false alarms. Figure 8 shows such parametric plots for the congruency effects in each of the three main experiments. Such graphs represent the cumulative percent of responding "yes" for each consecutive rating (rating 1, rating 2 or less, rating 3 or less). There is no point for the fourth rating because one must use one of the 4 ratings so the result always falls at the point (100, 100). If performance is at chance, the points fall on the positive diagonal; if performance is perfect, it falls in the upper left corner with 100% hits and 0% false alarms. Finally, if performance for a given rating is unbiased (probability of a "yes" is 0.5), then that point falls on the negative diagonal.

For all experiments, the three points on the ROC curve formed a negatively accelerated function that is typical of predictions from signal detection theory based upon comparing random variables to a decision criterion (Green & Swets, 1966). The ROCs clearly deviates from a linear function that is predicted by the high threshold theory (a line from $(0, x)$ to (100, 100) with x between 0 and 100) in which one guesses when not detecting the target. Thus, one can rule out a simple version of the high threshold model for these experiments.

The effect of congruency on the ROC is illustrated in Figure 8. Each panel shows the results of the dual-task condition broken down by congruent and incongruent trials. Only the dual-task conditions are shown because the congruency effect is larger for that condition than the single-task condition. The solid circles show performance for the congruent conditions and the open squares show performance for the incongruent condition. The congruency effects were consistently significant as reported in the body of the article. Here one can also see the ROCs were shifted between the congruent and incongruent conditions as expected for a change in sensitivity.

We can further break down the congruency effect into its components. For hits, the congruent target – target pair can be compared with an incongruent target – distractor pair. For correct rejections, the congruent distractor – distractor pair can be compared to the incongruent distractor– target pair. For targets, the effect of congruency on hits was 5±1, 8±1 and 3±3 for Experiments 1, 2, and 3, respectively. For distractors, the effect of congruency on correct rejections was 1±1, 5±3 and 0±1 for Experiments 1, 2, and 3, respectively. For individual experiments, these results were not significant. Instead, experiments were combined as if all the subjects were in one big experiment. The combined congruency effects for targets was a significant 6.7 ± 1.3% (95% CI 4.0, 9.4, $t(17) = 5.22$, $p<.001$, two tailed). The combined congruency effects for distractors was ~~a marginal~~ 3.1 ± 1.6% (95% CI -0.3, 6.4, $t(17) = 1.92$, $p=.071$, two tailed). The difference is a significant 3.6 ± 1.7% (95% CI 0.1, 7.1, $t(17) = 2.18$, $p=.043$, two tailed). In summary, this pattern is consistent with the congruency effect being larger for hits (two targets) relative to correct rejections (two distractors).

In our previous studies, we did not find consistent differences in congruency effects for target and distractors. In White et al. (2020), there were similar congruency effects for both hits and correct rejections. In Popovkina et al. (2021), there were what is called a *two-target effect* (Duncan, 1980): worse performance for hits with two targets (a negative congruency effect).