Spatial filtering is less selective for dual tasks than single tasks

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Last revised: January 1, 2024 (version 10) 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 (distractors) 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 distractor stimuli. Cues in the flanker paradigm include spatial location, but also often foveal positioning, the relative position within a multiple stimulus array (typically the center), and sometimes other stimulus properties such as color (Bundesen, 1984) or size (Lavie, 19[illegible]). 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 good 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 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 a 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 are accounted for by errors of selection. The locus of selection error, however, could be within early perceptual processing, such as with "imprecise targeting" as described by Bahcall & Kowler (1999), or alternatively, it could 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%.

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 ~~such as in theories of failed selection~~ within immediate processing ~~like~~ imprecise targeting ~~maintain~~, then there should be an advantage for the sequential condition over the simultaneous condition. Alternatively, if errors arise within some later process, such as the selection-by-decision hypothesis ~~maintains~~, 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 ~~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.

To further pursue the nature of spatial selectivity, we investigated whether errors in spatial filtering arise from a graded process such as attenuation of representations of stimuli in uncued locations (Treisman, 1960) or an all-or-none process such as blocking representations of uncued items from 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 attenuationand therefore that errors should decrease with increasing contrast of irrelevant stimuli. Alternatively, an all-or-none process like blocking cannot be overcome with increasing contrast and therefore any effect of increasing contrast on performance will asymptote with high contrasts. 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 [redacted]. And, finally, the errors arose due to an all-or-none mechanism such as blocking. 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. They also ruled out the possibility that the errors occurred due to do a graded process such as attenuation.

they showed that this difference in congruency effects for single and dual tasks was also obtained for discriminating between increments and decrements, ~~rather than simply detecting increments,~~ which do have dual-task deficits.

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. The observers were instructed to either make a single response to one of the digits (single-task condition), or to make two separate responses 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 more 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

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 experimentor 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 ("horizontal"). 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

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 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 kind of noise for stimuli with a wide range of spatial and temporal scales.

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 was 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 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 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 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%.

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 tested. 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 allows one 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 stimulus-driven 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 if 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

This result is consistent with the congruency effect being mediated by memory or decision rather than immediate processing such as stimulus-driven perceptual processes.

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%, (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%, (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 reliable. 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%, $t(5) = 15.47$, $p < .001$). 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 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 these experiments, the congruency effects remained, even for clearly visible stimuli with perfect performance in the congruent condition.

General Discussion

Summary of Main Results

Despite widely separated stimuli, three experiments revealed congruency effects for 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 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. 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) ~~that illustrate this distinction~~.

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 congruency or for single-versus-dual-task. Regarding the second response to the flankers on the dual-task trials, the congruency effect was about 250 ms (about 970 versus 1220 ms). 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 processing, and flanker paradigms, which reflect other forms of selection as well.

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 selection. A pure selection account, however, also has problems accounting for the entire 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 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 the single-task condition, however, only one stimulus is relevant to the task. Thus as soon as possible one can use an all-or-none selection process so that only the representation of the relevant stimulus is passed to memory and other later processes. In effect, selection protects the relevant representation from interaction with the irrelevant representation in the single task, but for the dual-task condition, both stimuli need to be processed in memory and therefore are impacted by interactive processing.

The two-process account 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 cross-talk that occurs. Thus, in the terms that we have been using, their model includes a graded selection mechanism. An advantage of the two-process hypothesis that we have proposed is that the all-or-none selection process 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 working 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 may be the use of a fixed order of responses versus an unpredictable order of responses. With a fixed order, one 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 tasks. 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 selection mechanism 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.

Bundesen 1994

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