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Absence of distracting information explains the redundant signals effect for a centrally presented categorization task☆

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The redundant signals effect, a speed-up in response times with multiple targets compared to a single target in one display, is well-documented, with some evidence suggesting that it can occur even in conceptual processing when targets are presented bilaterally. The current study was designed to determine whether or not category-based redundant signals can speed up processing even without bilateral presentation. Toward that end, participants performed a go/no-go visual task in which they responded only to members of the target category (i.e., they responded only to numbers and did not respond to letters). Numbers and letters were presented along an imaginary vertical line in the center of the visual field. When the single signal trials contained a nontarget letter (Experiment 1), there was a significant redundant signals effect. The effect was not significant when the single-signal trials did not contain a nontarget letter (Experiments 2 and 3). The results indicate that, when targets are defined categorically and not presented bilaterally, the redundant signals effect may be an effect of reducing the presence of information that draws attention away from the target. This suggests that redundant signals may not speed up conceptual processing when interhemispheric presentation is not available.

1. Introduction

The presence of redundant information within a display provides a stronger signal to which people respond more quickly than they would without redundancy (e.g., Miller, 1982; Raab, 1962). This has been demonstrated with simple response time (RT) tasks, choice RT tasks, and go/no-go tasks (Miller, 2004). It has been demonstrated both with signals in different modalities, such as one visual and one auditory stimulus (e.g., Diederich, 1995; Diederich & Colonius, 1987; Miller, 1982, 1986), and with unimodal signals, such as two visual stimuli (e.g., Forster, Cavina-Pratesi, Aglioti, & Berluchhi, 2002; Schwarz & Ischebeck, 1994), although the effect is sometimes dependent on displaying targets bilaterally (e.g., Corballis, Hamm, Barnett, & Corballis, 2002). Some evidence also suggests that the redundant signals effect can be elicited at more abstract levels of information processing, although the effect is sometimes confounded with an effect of removing nontarget stimuli. The current study was conducted to determine whether or not redundancy gain can occur in categorical processing, even without bilateral stimulus configurations, or if there will only be an advantage of removing nontarget stimuli and no advantage of adding an extra target.

Research has indicated multiple cognitive or neurological loci for the redundant signals effect in RT. Some researchers have found behavioral and neural evidence for the redundant signals effect in early visual processing (Corballis, 2002; Lobaugh, Chevalier, Batty, & Taylor, 2005; Miniussi, Girelli, & Marzi, 1998; Zehetleitner, Krummenacher, & Müller, 2009; but see Miller, Kühlwein, & Ulrich, 2004), even as early as the stage of sensory persistence (Savazzi & Marzi, 2008). Others have found evidence for the redundant signals effect at a later stage of processing (e.g., Iacoboni & Zaidel, 2003; Schwarz, 2006), with some specifically suggesting that the effect might occur at the response-selection level (e.g., Akyürek & Schubö, 2013; Miller, 1982). Schwarz (2006) argued that an increased redundant signals effect in people with split brains (e.g., Corballis et al., 2002; Roser & Corballis, 2002, 2003) is further evidence that the redundant signals effect occurs at post-perceptual levels. Roser and Corballis also presented evidence that the redundant signals effect in people with split brains did not depend on bilateral symmetry between redundant targets (Roser & Corballis, 2002), nor did it occur when a target stimulus was presented with a non-target stimulus (Roser & Corballis, 2003). They concluded that the redundant signals effect, at least in people with split brains, may occur at the level of response selection. Evidence seems to be opposed to the presence of a redundant signals effect in the speed of motor response execution

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(Miller, Ulrich, & Lamarre, 2001; Mordkoff, Miller, & Roch, 1996), although redundant signals may affect motor processing in ways not related to speed (Cavina-Pratesi, Bricolo, Prior, & Marzi, 2001; Diederich & Colonius, 1987; Giray & Ulrich, 1993; Plat, Praamstra, & Horstink, 2000).

Overall, the data suggest that the redundant signals effect can occur both in basic visual processing and in higher-level processing, including response-selection mechanisms. The question becomes in what higher-level processing mechanisms the redundant signals effect can be found; for example, is it possible for the redundant signals effect to occur in conceptual processing? If a redundant signals task is designed such that object categorization is needed to complete the task, then a significant redundant signals effect would indicate a speed-up in category-based decision making. Evidence from previous research suggests that categorization of visual objects occurs after early visual processing. The category of a visual stimulus, including letters, does not affect processing until after visual analysis (Pernet et al., 2003). Instead, Pernet et al. found N2 and P2 EEG components were the earliest to be affected by the category of a visual stimulus, suggesting that processing related to categories begins at the level of matching the stimulus to a representation. Additionally, Dick (1971) found that naming the category of a visual stimulus takes longer than naming its identity, and concluded that identification precedes categorization, a conclusion also reached in a review by Reed (1973). However, Posner (1970) and Taylor (1978) also found a faster RT for stimulus identification than for stimulus categorization, but concluded that identification and categorization occur as parallel, independent processes, given that RT for categorization tasks is not always affected by manipulations, such as acoustic similarity between letters, that affect RT in identification tasks. Regardless of their independence, categorization appears to be a consistently longer process than identification (Taylor, 1978). Additionally, at least for letters and digits, categorization effects can occur even for a target that is physically identical to an item in the opposite category (The letter O and the number 0; Jonides & Gleitman, 1972), leading Reed (1973) to conclude that categorization is not based on a particular conjunction of physical features that might differ between letters and numbers. All of the above evidence suggests that categorization occurs at a higher level than visual analysis, and that categorization is either a different and longer type of processing, or a higher level of processing than stimulus identification. Redundancy gain for categorical stimuli therefore would indicate a redundant signals effect not only beyond the level of early visual processing, but specifically within the level of stimulus categorization.

A few experiments that have been conducted to address this possibility indicate that a conceptual-level redundant signals effect may be possible, at least for bilateral target presentation. However, some of the experiments that have demonstrated an apparent redundancy gain in conceptual processing of visual stimuli may have confounded a favorable effect of redundancy with an unfavorable effect of distracting information. Marks and Hellige (2003) asked participants to read letter trigrams and number trigrams, presented unilaterally (single signals); or presented bilaterally (redundant signals), in either the same format or two different formats (upper and lower case for letter trigrams, digits and dot patterns for number trigrams). For letter trigrams, accuracy actually improved slightly when redundant trigrams were presented in different cases compared to identical cases; for number trigrams, accuracy decreased when redundant trigrams were presented in different format, but was still higher than for single trigrams. Marks and Hellige thus demonstrated that there is some effect of redundant signals at an abstract level of processing, although their paradigm did not lend itself to RT measures specifically.

There is also a possibility that Marks and Hellige did not actually find a benefit of redundancy, but instead found a benefit of removing irrelevant information from the display. In their single signal trials, noise stimuli were used for the positions that did not contain target stimuli. In the redundant signal trials, those noise stimuli were replaced with another set of target stimuli. As a result, redundant signals trials not only increased the number of target signals available, but also reduced the number of noise signals. In studies of specific (non-categorical) redundant signals, there is evidence that the redundant signals effect can be reduced by removing non-target signals from the single signal conditions (e.g., Miller, 1982), although eliminating nontargets does not always reduce the effect (Allen, Groth, Weber, & Madden, 1993; Grice & Canham, 1990). It is therefore possible that redundant signals trials were more accurate in Marks and Hellige (2003), not because the additional signal enhanced accuracy in redundant signal trials, but because the noise stimuli distracted participants and therefore reduced accuracy in single signal trials. Such an interpretation would not be surprising, given that irrelevant stimuli often degrade performance in responding to visual stimuli (e.g., Bjork & Murray, 1977; Eriksen & Eriksen, 1974).

Marks and Hellige (2003) examined the redundant signals effect with respect to accuracy rather than RT. Reinholz and Pollman (2007), however, did examine RT for bilaterally-presented redundant categorical targets. They asked participants to make speeded judgments about whether or not stimuli belonged to a particular category (either faces or buildings), and found that responses were significantly faster with redundant targets than with single targets. However, some caution is necessary in interpreting their results, as the target category switched between faces and buildings within participants. In the single signal trials, targets were sometimes paired with a scrambled stimulus and sometimes paired with a stimulus from the opposite target category (e.g., a face target would be paired with a building non-target). The only significant difference in RT was the difference between redundant targets and single target + other-category stimulus; the difference between redundant targets and single target + scrambled stimulus was not significant. This indicates that the effect on RT was not necessarily due to a redundancy-related decrease in RT, but may instead have been due to an increase in RT during single signal trials in which a previous target interfered with current target processing. Thus, Reinholz and Pollman's research, like that of Marks and Hellige (2003) may have shown an advantage of eliminating information that pulled attention away from the targets, rather than an advantage of additional targets in the display.

Other research, which also employed bilaterally-presented stimuli, suggests that face familiarity judgments can benefit from redundancy even when it takes the form of two different photographs of the same famous person (Mohr, Landgrebe, & Schweinberger, 2002; Schweinberger, Baird, Blümler, Kaufmann, & Mohr, 2003). Emotion recognition judgments may also benefit from bilateral redundancy, even when the redundancy is presented as two different faces expressing the same emotion (Tamietto, Adenzato, Geminiani, & de Gelder, 2007; Tamietto, Latini Corazzini, de Gelder, & Geminiani, 2005). Although not explicitly testing redundancy gain for discrete categories, these studies indicate that processing of bilaterally-presented categorical information is susceptible to redundancy gain.

Consequently, it appears likely that redundancy gain can occur for categorical stimuli. However, the experiments discussed above all employed bilateral redundant stimuli. In the case of non-categorical redundant signals, presenting multiple stimuli to one visual hemifield often does lead to redundancy gain, but redundancy gain is often stronger when stimuli are presented to separate visual hemifields (Corballis et al., 2002; Girard, Pelland, Lepore, & Collignon, 2013; Schulte, Pfefferbaum, & Sullivan, 2004; but see Ouimet et al., 2009). Additionally, experiments in which non-categorical targets are presented on the vertical midline of vision often show that what appears to be redundancy gain is mostly or entirely eliminated when noise stimuli are removed from single-signal conditions (Grice & Canham, 1990; Grice, Canham, & Boroughs, 1984; Grice & Gwynne, 1987; Grice & Reed, 1992), although some research shows a robust redundancy gain for vertical midline displays, regardless of noise (Allen, Weber, & Madden, 1994). These results indicate that the opportunity to begin processing of the redundant stimuli in two separate hemispheres may be a special case that maximizes the speed-up in RT. This may be due to the ability to process similar-format items without significant interference when the two items are presented to separate brain hemispheres rather than to the same hemisphere (Patel & Hellige, 2007). When two members of a category are presented on the vertical midline of vision, so that the two objects cannot begin processing entirely in separate hemispheres and interhemispheric coordination is needed to visually process a whole object (Abrams, Nizam, & Carrasco, 2012), it is not known if the redundancy will still convey an advantage in speeded responding.

Cases in which speeded processing is not actually attributable to redundancy, but only attributable to the absence of nontarget information; and cases in which the location of the targets may weaken redundancy gain; indicate that visual display redundancy may only be advantageous under strictly limited circumstances. The amount of abstract processing required to complete a task, combined with the configuration of the display, may determine whether or not participants can capitalize on redundancy to process information more efficiently. It is clear that specific-target processing sometimes benefits from redundancy in vertical midline configurations, but often does not; and that categorical processing may sometimes benefit from bilateral redundancy, but sometimes does not. However, the benefit of categorical redundancy in vertical midline presentations is open to question.

To address the question, the current study was designed to determine whether or not the redundant signals effect occurs for categorical stimuli in the absence of bilateral presentation, or if what appears to be redundancy gain in these cases is entirely attributable to distraction in the single-target conditions. Toward that end, participants in three experiments responded to categorical targets in a go/no-go task with stimuli presented above and below the center of a computer screen. In the first experiment, nontarget stimuli were present in the single-target trials; the next two experiments employed single-target trials without nontarget stimuli. Based on previous face recognition and emotion recognition studies, it was hypothesized that a redundant signals effect would occur regardless of the presence or absence of nontargets in the single-target condition. This would suggest that, even without separate-hemisphere processing of bilateral stimuli, presenting multiple targets enhances speeded processing of categorical information. By contrast, if only Experiment 1 showed significant redundancy gain, it would indicate that redundancy cannot enhance speeded categorical processing when it is presented on the vertical midline of vision. Instead, any apparent redundancy gain in Experiment 1 would be attributable to the absence of nontargets in redundant-signals trials.

Finally, there are two major classes of models that attempt to explain how the redundant signals effect occurs. Both classes of models assume that processing of multiple stimuli can occur in parallel, but differ on the source of information that contributes to a response. Race models suggest that the redundant signals effect is due to statistical facilitation (e.g., Raab, 1962). In race models, each target is processed separately in two different processing channels, and the two channels race against each other to elicit a response. The first stimulus that has reached the point at which it can elicit a response continues to be processed; other stimuli do not contribute to further processing. Because there is normal variation in speed of processing, increasing the number of channels increases the probability that one of the channels will be processed quickly. By contrast, coactivation models suggest that the information from redundant stimuli is combined during processing (e.g., Miller, 1982). Because increasing the number of targets increases the amount of information being contributed to processing, having more targets increases the speed with which sufficient information is processed to elicit a response.

Whether or not coactivation is evident seems to depend on the type of redundant signals. Some researchers have found that, when controlling for interstimulus contingencies, coactivation is only evident when the signals are combined within a single perceptual object and are presented in separate feature dimensions, such as when one signal is defined by orientation and one signal is defined by color (Akyürek & Schubö, 2013; Feintuch & Cohen, 2002; Mordkoff & Danek, 2011), although some researchers have found evidence of coactivation even with bilaterally separated targets (e.g., Miniussi et al., 1998; Savazzi & Marzi, 2008). Other researchers have found that even bilateral presentation is not necessary for coactivation to occur; Krummenacher, Müller, and Heller (2002) found that coactivation can occur with two separate targets in a visual search task, as long as the targets are close in space; and Schulte et al. (2004) found evidence for coactivation even with spatially separated but unilaterally presented targets, although the evidence for coactivation was greater in bilaterally presented targets. In the current study, because the redundant signals were spatially separated, not bilateral, and not defined in separate feature dimensions, it was hypothesized that the redundant signals effect would be attributable to a race between the redundant stimuli rather than coactive processing of the two stimuli.

In all three experiments, participants gave informed consent before participating. All experiments complied with the ethical standards outlined by the Helsinki Declaration and its amendments, and were approved by the Institutional Review Board of the University of Central Florida.

2. Experiment 1

Experiment 1 was designed to determine whether or not a redundant signals effect occurs with categorical signals and without bilateral presentation. To avoid target-switching effects, the target definition remained the same throughout the experiment; targets were always defined as any number.

2.1. Method

2.1.1. Participants

Fourteen participants (10 female, mean age = 18.21) recruited from the University of Central Florida Psychology Department subject pool participated for partial course credit. Participants had normal or corrected-to-normal vision.

Given that we were testing for the possible absence of an effect, we wanted to ensure that we had sufficient power to detect even a small difference in response times. Toward that end, we conducted a repeated-measures ANOVA power analysis in G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007), using a Cohen's f of 0.2, a power of 0.99, an alpha error probability of 0.05, no nonsphericity correction, and a correlation of 0.93 between repeated measures. The correlation coefficient was determined by a pilot study in which participants responded to gray squares presented singly or in pairs. Using the above parameters, 14 participants should be sufficient to detect a small effect in response times.

2.1.2. Apparatus and stimuli

The stimuli were presented on a Samsung SyncMaster 2233 22-in. LCD monitor and eye movements were recorded using an Eyelink 1000 eye tracking system (SR Research, Ottawa, Ontario) with the standard Eyelink desktop headmount. The primary purpose of the eye tracker was to use drift correction to encourage participants to focus in the center of the screen. The host computer was a Windows 7 Pro computer, with an Intel HD Graphics 2500 graphics driver (Intel, Santa Clara, California), and the stimulus computer was a Windows 7 Pro computer with a GeForce GT 440 graphics card (NVIDIA, Santa Clara, California). Responses were recorded on a Microsoft Sidewinder game controller.

Participants were instructed that any number was a target; the numbers employed in the experiment were 2 through 9. The experiment did not include 0 or 1 because of the possibility that they would be mistaken for letters. The letters A through H were used as distractors. In all trials, two black objects (letters and numbers) subtending 1° of visual angle were presented, centered at 3° above and below the center of a white screen.

2.1.3. Procedure

Participants were screened for normal or corrected-to-normal visual acuity and color vision, then completed a brief demographic questionnaire. They were then given computerized instructions. Participants were told to press the right trigger on their game controller if they saw a number, and to make no response if they did not see a number. They were instructed to respond as quickly as they could without making mistakes. After the instructions, the eye tracker was calibrated.

Participants completed 12 practice trials, followed by 5 experimental blocks of 32 trials each. At the beginning of each trial, drift correction was performed to force participants to focus on the center of the screen. Participants were not able to move forward in the trial until their eyes were focused in the center of the screen. After drift correction, a fixation cross subtending 1.4° of visual angle was presented for a random interval of 350–700 ms. The fixation cross then disappeared and two objects appeared on the screen. On 50% of the trials, both objects were letters (no signal condition), on 25% of the trials, one object was a letter and one object was a number (single signal condition), and on 25% of trials, both objects were numbers (redundant signal condition). In all trials, the two stimuli were non-identical, i.e., no trial contained two of the same letter or two of the same number. The search array was presented for 1500 ms, even if the participant responded in that time. Participants were able to respond until the search array was replaced by a brief blank screen.

2.1.4. Race model inequality analysis

Miller (1982) defined a boundary for race models:

$$P(RT < t \mid AB) \leq P(RT < t \mid A) + P(RT < t \mid B), \tag{1}$$

where $P(RT < t)$ is the probability that RT will be faster than time t, and A and B each refer to the presence of one target signal. In the current experiment, signal A is a single target located above the center of the screen, and signal B is a single target located below the center of the screen. If the probability of having made a response to redundant signals, $P(RT < t|AB)$, is anywhere greater than the summed probabilities of having made a response to either single signal, the race model inequality is violated. A violation indicates that the redundant signals effect is not simply due to statistical facilitation; instead, information from the two redundant signals is being combined during processing.

Ulrich, Miller, and Schröter (2007) outlined a Vincentizing method (Vincent, 1912) for testing the race model inequality. In this method, the researcher estimates the cumulative distribution function (CDF) of the redundant signals response times, which plots the probability that a response has occurred before time t. The researcher then estimates the upper boundary to the race model inequality (sum of the CDF of a single signal in location A plus the CDF of a single signal in location B). (Because it is the sum of two probability distributions, the race model inequality reaches a probability value of 2.0; Ulrich et al. only estimate the race model inequality up to a probability of 1.0 for the purposes of comparison.) Then, the RT associated with a set of quantiles of probability is calculated for both the redundant signals CDF and the upper race model bound. These calculations are performed separately for each participant.

The RTs for the redundant signals CDFs and the race model CDFs are then compared at each quantile across the entire group. Any quantile for which the redundant signals RT is significantly faster than the upper boundary of the race model inequality is interpreted as a violation of the race model inequality. In this study, we calculated the estimated CDFs using the formulae provided by Ulrich et al. (2007). The RTs for 4 quantiles (0.10, 0.15, 0.20, and 0.25) were compared for the redundant signals trials and the race model inequality using one-way, paired-samples t-tests with the Bonferroni correction for familywise error. This range of quantiles is suggested by Kiesel, Miller, and Ulrich (2007), because coactivation models are expected to violate the race model inequality at early rather than later RTs. As in Ulrich et al. (2007), any t-test in which the RT for redundant signals was significantly faster than the RT for the race model inequality was taken as a violation of the race model inequality, indicating coactivation.

2.2. Results

2.2.1. Response times

Because we employed a go/no-go task, RT analyses could only be performed on target-present trials. To test for the redundant signals effect, we compared mean RT for redundant signals to mean RT for each participant's faster single-target location. The favored single-target location for each participant was used to minimize the likelihood that any redundant signals effect was due to location uncertainty in the single-target trials. Although the mean RT of one location was faster than the mean RT of the other location, there was no participant for which one location was consistently faster than the other. Thus, a redundant signals effect that adheres to a race model should still be detectable using this method, since the non-favored location should still sometimes win a race over the favored location. We conducted a one-way, paired-samples t-test, using SPSS 21 for Windows with default settings. An alpha level of 0.05 was used for significance. RT is displayed in Fig. 1.

The effect of redundancy was significant, $t(13) = 6.74$, $p < 0.001$, $\eta^2 = 0.78$, such that RT was faster for redundant signal trials ($M = 461$ ms) than for single signal trials ($M = 493$ ms). The expected redundant signals effect was therefore present.

2.2.2. Accuracy

Accuracy analyses were performed on all four trial types, using a one-way (no signal vs upper single signal vs lower single signal vs redundant signals), within-subjects ANOVA. An alpha level 0.05 was used for significance. Because Mauchly's test indicated that sphericity was violated, $\chi^2(5) = 26.933$, $p < 0.001$, the Greenhouse-Geisser correction for degrees of freedom was employed. The effect of trial type was not significant, $F(2.01, 26.06) = 3.288$, $p = 0.053$, partial $\eta^2 = 0.202$, $M_{\text{nosignal}} = 98.21\%$, $M_{\text{uppersingle}} = 99.29\%$, $M_{\text{lowersingle}} = 99.64\%$, $M_{\text{redundant}} = 99.82\%$.

Additionally, a one-way ANOVA was performed to compare redundant signals accuracy to accuracy for the faster single signal location. The difference was not significant, $F(1,13) = 1.00$, $p = 0.336$, partial $\eta^2 = 0.071$, $M_{\text{redundant}} = 99.82\%$, $M_{\text{fastersingle}} = 99.29\%$. Thus, the redundant signals effect was not attributable to a speed-accuracy trade-off.

2.2.3. Race model inequality

Four Bonferroni-corrected, one-tailed, paired-sample t-tests were

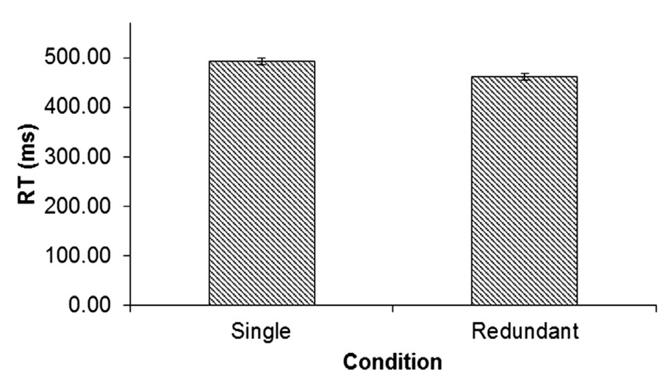

Fig. 1. Mean response times for the faster single signal location and for redundant signals in Experiment 1. Error bars represent 2 within-subjects standard errors above and below the mean, based on the correction to Cousineau (2005) outlined in Morey (2008).

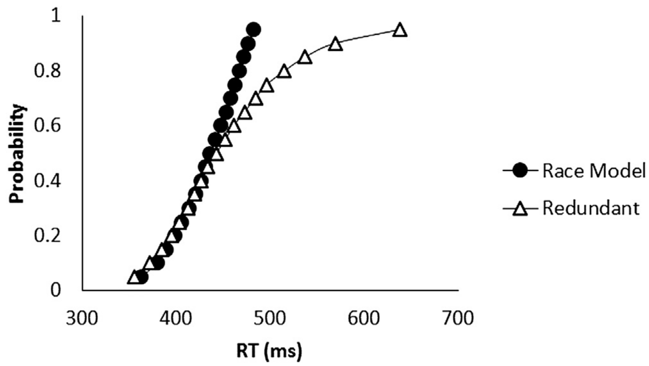

Fig. 2. Cumulative distribution functions for the redundant signals condition (white triangles) and the upper bound of the race model inequality (black circles) in Experiment 1. Although the bound for the race model inequality continues up to a probability of 2.0, it does not need to be tested above a probability of 1.0, as outlined by Ulrich et al. (2007). The race model inequality is violated when the redundant signals distribution is significantly to the left of the upper bound for the race model inequality.

performed to determine if RTs in the redundant signal trials were faster than predicted by the race model inequality. The upper bound for the race model inequality was calculated by summing the cumulative distribution functions for the two single signal locations. An alpha level of 0.05 was used for significance, so that the Bonferroni-corrected alpha level for each individual *t*-test was 0.0125. RTs for the redundant signals condition and the race model inequality are displayed in Fig. 2. At 0.10 probability, there was a trend toward coactivation, $p = 0.071$, but it was not significant, and the other three quantiles did not show even a marginally significant trend toward redundancy gain, $p > 0.219$ for all. As Kiesel et al. (2007) argued, researchers should be cautious about accepting a significant difference between redundant signals and the race model inequality for only a single quantile as evidence for coactivation. Given that only one quantile even approached significance, and would not have reached significance even if a Type I error correction were not employed, we concluded that there was no evidence of coactivation in Experiment 1.

2.3. Experiment 1 discussion

In Experiment 1, participants responded to redundant targets more quickly than to single targets, even though targets were defined as members of a category of objects (numbers) instead of as a specific object (e.g., the number 2), and even though no redundant signals trial ever contained two of the same number. Because categorization was required to determine whether or not each object was a target, Experiment 1 may have provided evidence that the redundant signals effect may occur in conceptual processing, even in the absence of bilateral visual presentation, suggesting that separate-hemisphere processing may not be solely responsible for the effect. In addition, the results could not be explained by target-switching costs in the single signal trials, because the target definition remained the same throughout the experiment. Finally, there was no evidence that redundant signals were processed coactively, indicating that the effect could be explained as a race between the two signals.

However, as discussed in the introduction, the results of Experiment 1 could be explained as a distraction-reduction effect rather than as a race between two signals. Nontargets were present in the single signal condition, but not in the redundant signal condition. It is therefore possible that participants did not speed up in redundant signals trials because there were two signals, but instead slowed down in single signal trials because there was distracting information. Experiment 2 was designed to determine whether or not the redundant signals effect still occurs for number categorization when the single-signal condition contains no nontargets.

3. Experiment 2

Experiment 1 provided possible evidence of a redundant signals effect for categorical targets. However, because nontargets were present in the single signal trials but not in the redundant signal trials, there may have been no real benefit of categorical redundancy. Instead, the speed-up in redundant signals trials could have been due to the absence of distracting information. To control for the distraction-reduction effect, Experiment 2 contained no letters in the single signal trials.

3.1. Method

3.1.1. Participants

Seventeen participants (13 female, mean age = 18.75) recruited from the University of Central Florida Psychology Department subject pool participated for partial course credit. Participants had normal or corrected-to-normal vision. One participant was excluded because the eye tracker could not be calibrated; 16 participants were included in the analysis.

3.1.2. Apparatus and stimuli

The apparatus and stimuli in Experiment 2 were similar to Experiment 1, with the exception of the number of stimuli. In 25% of the trials, there was 1 letter in the array (single non-signal); in 25% of the trials, there were 2 letters in the array (double non-signal); in 25% of the trials there was 1 number in the array (single signal); and in 25% of the trials, there were 2 numbers in the array (redundant signals). Thus, there were no distracting letters in the single signal condition; additionally, 1-object arrays were equally likely to contain a target or no target, and 2-object arrays were also equally likely to contain a target or no target. In the single non-signal and single-signal trials, the location of the object was randomized, with the object appearing equally often above and below the center of the screen. As in Experiment 1, objects were placed 3° above and below the center of the screen, and all two-object trials contained two non-identical objects, such that no trial ever contained two of the same letter or two of the same number.

3.1.3. Procedure

The procedure was the same as Experiment 1. Participants completed 12 practice trials, followed by 5 experimental blocks of 32 trials each.

3.2. Results

3.2.1. Response times

As in Experiment 1, a one-way, paired-samples *t*-test was employed to compare redundant signals RT to the RT for the faster single signal location. Mean RT is displayed in Fig. 3. Response times for redundant signals ($M = 446$ ms) were not significantly different from single signal trials ($M = 444$ ms), $t(14) = 0.34$, $p = 0.370$, $\eta^2 = 0.008$. Thus, there was no redundant signals effect in Experiment 2.

Additionally, a 2 (number of targets; within-subjects) × 2 (experiment; between-subjects) mixed-method ANOVA was conducted to compare Experiment 1 to Experiment 2. The main effect of number of targets was significant, $F(1,27) = 10.11$, $p = 0.004$, partial $\eta^2 = 0.272$, such that participants responded more quickly to redundant targets ($M = 454$ ms) than to single targets ($M = 467$ ms). The main effect of experiment was not significant, $F(1,27) = 1.02$, $p = 0.321$, partial $\eta^2 = 0.04$. Importantly, the interaction of number of targets and experiment was significant, $F(1,27) = 14.06$, $p = 0.001$, partial $\eta^2 = 0.34$. Post-hoc tests of the simple effect of number of targets indicated that only Experiment 1 had a significant redundancy gain, $p < 0.001$ for Experiment 1, $p = 0.685$ for Experiment 2. Because there was no significant redundancy gain in Experiment 2, coactivation analyses are not discussed.

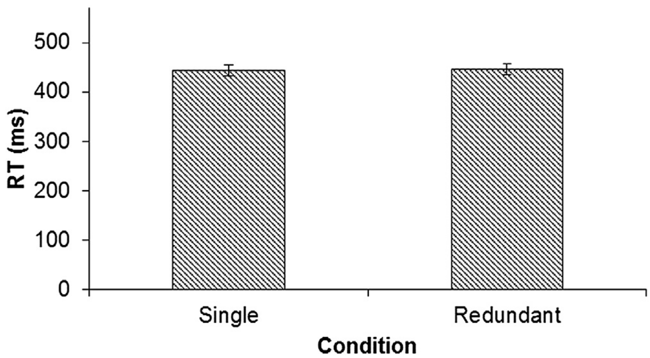

Fig. 3. Mean response times for the faster single signal location and for redundant signals in Experiment 2. Error bars represent 2 within-subjects standard errors above and below the mean, based on the correction to Cousineau (2005) outlined in Morey (2008).

3.2.2. Accuracy

A one-way (upper non-signal vs lower non-signal vs double non-signal vs upper single signal vs lower single signal vs redundant signals) within-subjects ANOVA was conducted on accuracy. Because Mauchly's test indicated that sphericity was violated, $\chi^2(14) = 58.65, p < 0.001$, the Greenhouse-Geisser correction for degrees of freedom was employed.

The effect of trial type was significant, $F(1.77, 24.76) = 4.63, p = 0.023$, partial $\eta^2 = 0.248$, $M_{\text{uppernonsignal}} = 97.33\%$, $M_{\text{lowernonsignal}} = 96.33\%$, $M_{\text{doublenonsignal}} = 97.33\%$, $M_{\text{uppersingle}} = 99.67\%$, $M_{\text{lowersingle}} = 99.67\%$, $M_{\text{redundant}} = 100.00\%$. To compare redundant signals accuracy to upper single signal accuracy and lower single signal accuracy, two post-hoc, paired-sample *t*-tests were conducted with the Bonferroni correction for familywise error. The difference was not significant, $p = 0.334$ for both tests.

Additionally, one-way ANOVA was conducted to compare accuracy on redundant signals trials to accuracy for the faster single signal location. The difference was not significant, $F(1,14) = 1.00$, $p = 0.334$, partial $\eta^2 = 0.067$, $M_{\text{redundant}} = 100.00\%$, $M_{\text{fastersingle}} = 99.67\%$. Thus, the lack of a redundant signals effect cannot be explained as a speed-accuracy trade-off between single and redundant signals.

3.3. Experiment 2 discussion

Experiment 2 was designed to address the possibility that what appeared to be a redundant signals effect in Experiment 1 could be explained by the absence of nontargets rather than the presence of two targets. There was no redundant signals effect evident in Experiment 2. This result indicates that the significant effect in Experiment 1 may not have been due to accelerated processing caused by redundant signals; instead, the presence of nontargets may have decelerated processing in the single signal trials.

Another possibility is that there was a ceiling effect in Experiment 2, which prevented the redundant signals effect from being significant. Given that there were multiple possible targets (all of the digits between 2 and 9), RT was very fast (444 ms for the faster single target location; 446 ms for redundant targets), and well below the RT for a similar number of possible targets in Sternberg's (1969) study. The redundant signals effect might therefore become significant if the task were made more difficult. However, other experiments have employed similarly simple tasks, such as letter recognition (e.g., Allen et al., 1993; Allen et al., 1994; Grice & Canham, 1990; Grice, Canham, & Gwynne, 1984; Grice & Gwynne, 1987; Grice & Reed, 1992) to test for redundancy gain, and have not indicated ceiling effects in RT. Nevertheless, to address the possibility that a more difficult task would show redundancy gain, Experiment 3 was designed to make it more difficult to detect a target.

4. Experiment 3

Experiment 3 was designed to make target detection more difficult than Experiment 2, to determine whether or not the categorical redundant signals effect occurs when response times are slower overall. Toward that end, orientation was added to the target definition as such that only numbers that were tilted 45° to the left were targets. Orientation has been used in the past to increase the difficulty of identifying targets in redundancy gain experiments (Bucur, Madden, & Allen, 2005). Additionally, to avoid nontarget effects, Experiment 3 maintained the no-nontarget design of Experiment 2.

4.1. Method

4.1.1. Participants

Nineteen participants (15 female; mean age = 19.47) participated for partial credit in an undergraduate psychology course. One participant was excluded because the computer running the experiment crashed; 2 more were excluded because the eye tracker could not be calibrated. Sixteen participants were included in data analysis.

4.1.2. Apparatus and stimuli

The apparatus and stimuli were similar to Experiment 2, except that the numbers and letters were rotated 45° to the left and right; participants were instructed to respond only to left-tilted numbers, and not to respond to right-tilted numbers or to letters in either orientation. Additionally, because the number 6 could be confused with a rotated number 9, the numbers 1, 2, 3, 4, 5, 7, and 8 were employed as targets, and the letters A through G were employed as distractors. The stimuli were created in Calibri font so that the number 1 would not be confusable with the lowercase letter l.

To maintain an equal number of each type of distractor, the proportion of distractors to targets increased. Each block contained 12.5% of each of the following conditions: 1 right-tilted letter, 1 left-tilted letter, 1 right-tilted number (single non-signal conditions), 2 right-tilted letters, 2 left-tilted letters, 2 right-tilted numbers (double non-signal conditions), 1 left-tilted number (single signal), and 2 left-tilted numbers (redundant signals). As in Experiment 2, the location of the object in single-object trials was randomized, with objects appearing equally often above and below the center of the screen. As in Experiments 1 and 2, objects were placed 3° above and below the center of the screen, and no two-object trial contained two of the same letter or two of the same number.

4.1.3. Procedure

The procedure was the same as Experiments 1 and 2, except that the blocks were longer to accommodate the greater proportion of distractors. Each participant completed 24 practice trials, followed by 5 blocks of 48 experimental trials.

4.2. Results

4.2.1. Response times

A one-way paired-samples *t*-test was conducted on redundant signals RT and RT for the faster single signal location to test for the redundant signals effect. Mean RT is displayed in Fig. 4. Response times for redundant signals trials ($M = 526$ ms) were not significantly different from response times for single signal trials ($M = 527$ ms), $t(15) = 0.09$, $p = 0.463$, $\eta^2 < 0.01$. Thus, making the target detection task more difficult did not lead to a redundant signals effect. Because there was no redundancy gain, coactivation analyses are not discussed.

4.2.2. Accuracy

A one-way (upper non-signal vs lower non-signal vs double non-signal vs upper single signal vs lower single signal vs redundant signals) within-subjects ANOVA was conducted on accuracy. Because Mauchly's test

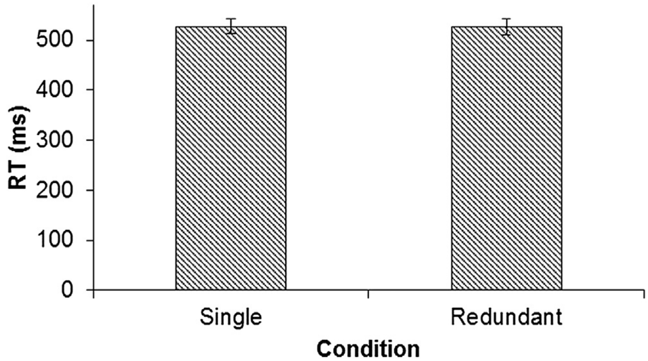

Fig. 4. Mean response times for the faster single signal location and for redundant signals in Experiment 3. Error bars represent 2 within-subjects standard errors above and below the mean, based on the correction to Cousineau (2005) outlined in Morey (2008).

indicated that sphericity was violated, $\chi^2(14) = 51.92$, $p < 0.001$, the Greenhouse-Geisser correction for degrees of freedom was employed. The effect of trial type was not significant, $F(1.79, 26.85) = 0.11$, $p = 0.881$, partial $\eta^2 = 0.01$, $M_{\text{uppernonsignal}} = 98.19\%$, $M_{\text{lowernonsignal}} = 98.47\%$, $M_{\text{doublenonsignal}} = 98.26\%$, $M_{\text{uppersingal}} = 97.92\%$, $M_{\text{lowersingle}} = 97.92\%$, $M_{\text{redundant}} = 98.54\%$.

Additionally, a one-way ANOVA was conducted to compare accuracy on redundant signals trials to accuracy for the faster single signal location. The difference was not significant, $F(1, 15) = 0.75$, $p = 0.401$, partial $\eta^2 = 0.05$, $M_{\text{redundant}} = 98.54\%$, $M_{\text{single}} = 97.50\%$. Thus, the lack of a redundant signals effect is not attributable to a speed-accuracy trade-off.

4.3. Experiment 3 discussion

Experiment 3 was designed to determine whether or not the redundant signals effect occurs for categorical targets, when the task is made more difficult by including orientation in the target definition. RT was not faster for redundant signals trials than for single signal trials, indicating no categorical redundant signals effect. The lack of a redundant signals effect in Experiment 2 therefore appears not to be the result of a ceiling effect. Consequently, Experiment 3 provides further evidence that, without bilateral presentation, the categorical redundant signals effect is attributable to the absence of distracting information.

5. General discussion

Although a large body of research has established the existence of a redundant signals advantage in response time, including in post-perceptual processing (e.g., Akyürek & Schubö, 2013; Iacoboni & Zaidel, 2003; Miller, 1982; Schwarz, 2006), the possibility of a redundant signals effect in categorical processing is less well-established. The research that has been performed indicates a redundant signals effect in speed and accuracy for bilaterally presented categorically-defined stimuli (Marks & Hellige, 2003; Mohr et al., 2002; Reinholz & Pollman, 2007; Schweinberger et al., 2003; Tamietto et al., 2007, 2005), but it is not known if two categorical targets can elicit a redundant signals effect without bilateral presentation. To address the possibility, the current study was designed to determine whether or not the redundant signals effect occurs when categorical targets are presented along a vertical line in the center of the field of view. A significant redundant signals effect occurred only when single signal trials contained a target stimulus paired with a nontarget stimulus. Additionally, there were no significant violations of the race model inequality, indicating that statistical facilitation was sufficient to explain the speed-up in response times associated with redundant signals compared to single signals with nontargets. The results suggest that redundancy in centrally-presented categorical targets can sometimes speed up response times, but that the effect is attributable to the attenuation of distraction compared to single signal trials. Previous research using non-identical, specific redundant targets (e.g., a target defined by color and another target defined by orientation; Krummenacher et al., 2002) has indicated that the redundant signals effect and coactivation can occur with non-identical targets. This suggests that the results of the current study are not due to the fact that the targets were not visually identical.

Our evidence suggests that the categorical redundant signals effect found by previous researchers may apply only to certain target arrangements. Specifically, processing of two targets that have begun visual processing in separate hemispheres may be a special case, as the categorical redundant signals effect occurs with bilateral target presentation. Additionally, two signals presented within a single object may elicit a redundant signals effect even when one signal is categorical (Selcon, Taylor, & Shadrake, 1991). In contrast, when two categorically-defined targets are presented as separate perceptual objects, and they are not presented bilaterally, it appears that redundancy conveys no advantage in categorical processing unless the second target replaces a nontarget. An interhemispheric advantage in categorical processing is consistent with the increase in redundancy gain for bilateral presentation evident in non-categorical target detection (Girard et al., 2013; Schulte et al., 2004). However, the categorical redundant signals effect could also sometimes be attributable to reduced distraction even with bilateral presentation. Reinholz and Pollman's (2007) redundant signals effect appeared to be due to interference in single-target trials, when the target was paired with a stimulus that belonged to a previous target category. Marks and Hellige's (2003) redundant signals effect could also have been due to noise, as the single-target stimuli were always paired with noise stimuli.

The current study provides direct evidence that the categorical redundant signals effect is limited in scope, although further research is needed to define its limits. One question is whether or not two categorical targets presented entirely to one visual hemifield would elicit redundancy gain. Redundancy gain is often weaker for unilaterally-presented specific targets than for bilaterally-presented specific targets (e.g., Corballis et al., 2002; Girard et al., 2013; Schulte et al., 2004; but see Ouimet et al., 2009), and preliminary evidence suggests that redundancy gain does occur for bilateral but not for unilateral targets in a letters-vs-digits categorization task (Mishler & Neider, 2017), suggesting again that bilateral presentation is optimal even for categorical processing.

However, a further question is whether or not less narrowly-defined categories would elicit a redundant signals effect and if the effect would be subject to the same limits. In the current study and in Mishler and Neider (2017), the targets were single-digit numbers, which are limited in number and are highly familiar stimuli to the participants. As a result, it may have been possible for participants to treat the targets as a small set of specific targets rather than as an entire category. Future research employing larger and less well-practiced categories could indicate that some categorization tasks can occur in the absence of bilateral presentation. It could also indicate either that redundancy is not useful even when it serves to reduce distraction, or that the additional difficulty of the task renders redundancy useful even when it does not serve to reduce distraction. Category typicality of target signals might also affect whether or not redundancy provides an advantage in speed or accuracy.

Additionally, Experiment 3 employed a visual dimension, orientation, to increase task difficulty. Given that orientation takes longer to process than the name of an alphanumeric character (Corballis, Zbrodoff, Shetzer, & Butler, 1978) it is possible that a redundant signals effect in categorization was suppressed by the need to determine orientation before determining whether or not a target was present. However, categorizing a character as a letter or digit also takes longer than naming the character, and this relationship is not affected by orientation (White, 1980), which may minimize the need to wait for orientation processing to finish before making a response, especially because the current study employed coarse left/right discriminations rather than requiring participants to distinguish between several different orientations as Corballis et al. (1978) did. Nevertheless, further research should employ cognitive manipulations of difficulty to determine if a redundant signals effect occurs for visually easy but cognitively difficult categorization tasks. Finally, Selcon et al. (1991) showed that pairing a categorical target with a non-categorical signal within the same perceptual object (i.e., presenting words in specific colors during a word categorization task) can lead to a redundant signals effect. Pairing target categories within a single object might therefore elicit a redundant signals effect that cannot be attributed to distraction in the single-target conditions. Within-object redundancy in non-categorical tasks does also tends elicit coactive processing of the target signals (Akyürek & Schubö, 2013; Feintuch & Cohen, 2002; Mordkoff & Danek, 2011); it is therefore possible that two categorical signals within one object would also show evidence of coactive processing.

Regardless, the current study indicates that not all forms of redundant target presentation will enhance target detection performance when participants must determine the category of a stimulus. Early processing in two separate hemispheres may be a special case that allows for enhanced categorization performance, although further research is needed to clarify whether or not the categorical redundant signals effect exists at all, or if it is simply a distraction-reduction effect.

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