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# Redundancy gain for categorical targets depends on display configuration and duration

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**ABSTRACT**
Redundancy gain is an improvement in speeded target detection when the number of targets associated with a single response is increased within a single display. The effect has been clearly demonstrated with specific targets, but it is not clear if it occurs in categorization tasks with non-identical targets. The current study tested the effect of target redundancy on speed and accuracy in a go/no-go categorization task. Targets were digits tilted 45° to the left, and were displayed in unilateral, bilateral, or central displays for either 1500 ms or 100 ms. Redundancy gain only occurred for brief targets displayed bilaterally in the upper visual field. The results indicate that redundancy gain is possible for categorization tasks with some bilateral configurations, supporting a role for interhemispheric processing in redundancy gain. Additionally, the results may indicate that processing strategies mask redundancy gain when participants can view targets for a long period of time.

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Redundancy gain; redundant signals effect; categorization; display configuration; display duration

The redundant signals effect, or redundancy gain, is an increase in speeded target detection performance associated with an increased number of target signals within a display (e.g., Miller, 1982; Raab, 1962; Todd, 1912). Improved performance is manifested as faster reaction times (e.g., Diederich, 1995; Diederich & Colonius, 1987; Hershenson, 1962; Miller, 1982; Raab, 1962; Todd, 1912) or as increased accuracy (e.g., Duncan, 1980; Egeth, Folk, & Mullin, 1989; Hellige & Marks, 2001; Marks & Hellige, 1999, 2003; Mohr, Pulvermüller, Mittelstädt, & Rayman, 1996; Mohr, Pulvermüller, & Zaidel, 1994). There is also evidence that redundancy can increase the force with which a motor response is made (Giray & Ulrich, 1993) or the speed with which response force is developed (Plat, Praamstra, & Horstink, 2000).

A considerable amount of research has been conducted to determine the level of processing at which the redundant signals effect occurs, and results seem to indicate that redundancy enhances processing performance at multiple levels. Evidence of redundancy gain in early perceptual processing comes from Savazzi and Marzi (2008), who found that the robustness of the redundant signals effect depended on the intensity and duration of brief visual stimuli. Additionally, early event-related potential (ERP) components show decreased latency in response to redundant signals (Lobaugh, Chevalier, Batty, & Taylor, 2005; Miniussi, Girelli, & Marzi, 1998). The effect may occur in higher levels of processing as well, such as the level of choosing a response (e.g., Akyürek & Schubö, 2013; Miller, 1982; Roser & Corballis, 2002, 2003), determining whether or not a word or words rhyme with a probe word (Banich & Karol, 1992), and drawing on semantic memory (Fiedler, Schröter, & Ulrich, 2013; Schröter, Bratzke, Fiedler, & Birngruber, 2015). However, further work is still needed to determine what types of higher-level processing can benefit from redundancy, and under what circumstances. The purpose of the current paper is to examine the effect of redundancy in different display configurations on the processing of stimulus categories.

Some studies already argue that categorical processing can be enhanced by redundancy, although the evidence in favour of the argument is ambiguous. Marks and Hellige (2003) found that participants could more accurately report brief letter trigrams if two trigrams were displayed, even when one trigram was uppercase and one was lowercase. They found the same for number trigrams, even when one

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trigram was displayed in Roman numerals and one was displayed in dot patterns. However, their single-trigram displays had a noise trigram (XXX or 888) in the position that did not contain a target, whereas redundant-trigram trials had no noise trigrams. Given that non-categorical redundancy gain is often weakened by removing noise from the single-signal condition (e.g., Grice, Canham, & Gwynne, 1984; Grice & Gwynne, 1987; Miller, 1982), it is possible that Marks and Hellige's apparent redundancy gain was actually an effect of having no noise in redundant-trigram trials; the same could be true of Shepherdson and Miller's (2014) redundancy gain for categorical processing of words. Reinholz and Pollman (2007) also found possible evidence of a categorical redundancy gain in response times when participants were asked to respond to either faces or buildings. However, participants only responded more quickly to redundant-target displays than to single-target displays that contained the previous target category in the non-target position (e.g., the target category was "buildings" in the previous block, the current target category was "faces," and participants saw a face paired with a building). Their results may therefore not have been due to target redundancy, but instead due to interference from previous target categories in single-target trials.

Some other experiments have shown evidence of redundancy gain in a categorization task or lexical decision task, but employed identical stimuli for their redundant-target conditions (Hasbrooke & Chiarello, 1998; Mohr, Endrass, Hauk, & Pulvermüller, 2007; Mohr et al., 1994, 1996). It is possible that redundancy gain in these cases is attributable to basic visual redundancy rather than semantic redundancy; such a possibility was mentioned by Hasbrooke and Chiarello (1998), who found redundancy gain occurred even for nonwords in a lexical decision task (although others have found no redundancy gain for nonwords; Mohr et al., 1994, 1996; Mohr et al., 2007). Still other experiments have shown no clear evidence of redundancy gain, or even a redundancy loss, for semantic categorization of words (Egeth et al., 1989; Mullin & Egeth, 1989; Zaidel & Rayman, 1994). It is therefore still unclear whether categorical processing can benefit from target redundancy and, if so, under what conditions redundancy will be useful.

Additionally, most of the above categorization and semantic processing studies employed bilateral redundancy, in which one signal was presented to each hemisphere, and the redundant signals effect was interpreted in terms of an advantage afforded by the opportunity for interhemispheric processing. Although some research has indicated that presenting both signals to one hemisphere does not affect redundancy gain (e.g., Marks & Hellige, 1999), or can even enhance redundant target processing (Banich & Karol, 1992), other research suggests that unilateral redundancy does not increase performance as much as bilateral redundancy (e.g., Girard, Pelland, Lepore, & Collignon, 2013; Schulte, Pfefferbaum, & Sullivan, 2004). One question that still needs to be answered is whether interhemispheric processing is important for categorical redundant signals effects, or if other display configurations can still enhance categorical processing. Some preliminary evidence may come from Mishler and Neider (2016), who presented categorically-defined, non-identical targets along an imaginary vertical line in the centre of the visual field, and found that redundancy gain for number categorization and teddy bear categorization did not occur when the single-target trials had no noise in them. However, Mishler and Neider (2016) did not test other display configurations, such as unilateral displays. Processing seems to be slowed for stimuli placed on the vertical centre line of vision, especially for items in the upper visual field (Abrams, Nizam, & Carrasco, 2012; Carrasco, Giordano, & McElree, 2004; Corbett & Carrasco, 2011). Presenting items specifically along the vertical centre line may therefore change visual processing, and could have prevented the redundant signals effect from occurring for Mishler and Neider (2016).

The evidence for categorical redundancy gain is not entirely clear and needs to be further explored. If categorical redundancy gain does occur, it also remains to be seen how redundant signals enhance target detection performance. Two major classes of models are most commonly used to explain the redundant signals effect. In race or statistical facilitation models (e.g., Raab, 1962), it is suggested that the two (or more) targets are processed in parallel; the fastest-processed target is the one that triggers a response. In coactivation models (e.g., Miller, 1982), the targets are also processed in parallel, but the processing is combined so that more information is contributing towards the selection of a response. Some researchers have found that coactivation occurs only when the redundancy occurs within a single object, for example, when participants can respond to either a certain colour or a certain shape, and one object is both the correct colour and the correct shape (Akyürek & Schubö, 2013; Feintuch & Cohen, 2002; Mordkoff & Danek, 2011), although other studies seem to suggest that coactivation can occur with two separate redundant objects (Krummenacher, Müller, & Heller, 2002; Miniussi et al., 1998; Savazzi & Marzi, 2008).

Why would coactivation not always be evident for two separate targets, if the presence of a separate non-target can affect response times to a target? It is possible that such target-detection tasks rely on a limited-capacity system, whereby a non-target stimulus, although not processed in conjunction with the target, would be processed in parallel with the target, increasing the load on the processing system and therefore slow target processing (e.g., Harding et al., 2016; Townsend & Nozawa, 1995, 1997). Further, the idea of such an independent, parallel, and limited-capacity system could be consistent with the results of Marks and Hellige (2003) and Shepherdson and Miller (2014) without necessitating redundancy gain had single-target displays not included an accompanying non-target. Two targets could potentially increase load on the processing system, leading to slower processing, but still race against each other. This could result in redundant-target processing that is faster than single-target-plus-non-target processing, given that there is no race between the single target and the non-target; but also result in redundant-target processing that is no faster than single-target-alone processing.

The current study was designed to address several questions. First, can the redundant signals effect occur for non-identical, categorically defined targets in the absence of noise; is the categorical redundant signals effect truly a gain due to categorical redundancy, and not a gain due to basic visual similarity or to noise reduction? Second, does the categorical redundant signals effect rely on interhemispheric processing; that is, does it rely on presenting two targets to different visual hemifields? Third, if there is a categorical redundant signals effect, is it attributable to coactive processing of the redundant signals, or is a race model sufficient to explain the effect? Toward that end, participants completed a go/no-go task in which they pressed a button in response to any left-tilted digit. In order to avoid the problem of basic visual redundancy, all redundant-stimulus trials contained two non-identical characters of the same category (digits or letters). Additionally, the two characters were always tilted in the same direction, to avoid the possibility that participants could make a decision about the number of targets in a trial based on heterogeneity of orientations within a display. In order to examine the effect of display configuration, redundant characters were presented unilaterally, bilaterally, or on the vertical centre line. Given that previous research indicates a possible redundancy gain for categorization tasks, it was expected that redundancy gain would occur for bilateral stimuli; however, because previous research suggests stronger redundancy gain for bilateral stimuli and our previous research suggests no redundancy gain for vertical centred stimuli, it was expected that redundancy gain would not occur for other display configurations. Finally, it was expected that a race model would suffice to explain any redundant signals effect found in the current study.

## Experiment 1

### Method

#### Participants

Sixteen participants (9 female, mean age = 18.56) were recruited from the University of Central Florida Psychology Department subject pool and participated for partial course credit. One participant was excluded because the experiment programme crashed; 15 participants were included in data analysis.[1] All participants had normal or corrected-to-normal near visual acuity and colour vision.

#### Apparatus and stimuli

The experiment was conducted on a Windows 7 Pro computer with a GeForce GT 440 graphics card (NVIDIA, Santa Clara, California) and a Samsung SyncMaster 2233 22-inch LCD monitor. To help participants maintain visual focus on the centre of the screen, eye movements were recorded by an Eyelink 1000 eye tracker (SR Research, Ottawa, Ontario) with a desktop headmount. Drift correction was performed at the beginning of each trial to make fine corrections to the eye tracker calibration and return the participant's eyes to the central fixation point. The eye tracker host computer was a Windows 7 Pro computer with an Intel HD Graphics 2500 graphics driver (Intel, Santa Clara, California). Participants used a Microsoft Sidewinder game controller to respond.

The stimuli were numbers 1, 2, 3, 4, 5, 7, and 8, and capital letters A through G presented in black Calibri font on a white background, rotated 45° to the left and right, and subtending 1° of visual angle. Any number rotated to the left was a target; all right-rotated numbers and all left- and right-rotated letters were non-targets. Previous, unpublished data from our lab indicated that there may be a ceiling effect for categorizing digits in distractor-free displays; orientation was added to the target definition to make the task more difficult. Stimuli were presented in five different configurations. In central trials, stimuli were placed in the centre of vision, with the centre of the stimulus 3° above and below the centre of the screen. In bilateral trials, stimuli were placed 3° to the left and right of centre, and either 3° above (bilateral top) or 3° below (bilateral bottom) the centre of the screen. In unilateral trials, stimuli were placed 3° above and below centre, and either 3° to the left (unilateral left) or 3° to the right (unilateral right) of centre. In all trials, either one or two objects were presented.

### Procedure

Before the experiment, participants were screened for normal or corrected-to-normal vision and given a brief demographics questionnaire. They were then given computerized instructions, in which they were told to press the right trigger on their game controller if they saw any left-rotated number, and to make no response if they saw no left-rotated number. The experimenter then calibrated the eye tracker and the participant completed one block of 40 practice trials before beginning the experimental blocks.

There were three sets of five experimental blocks; each set contained a single block each of central, bilateral top, bilateral bottom, unilateral right, and unilateral left stimulus configurations. Each block contained 40 trials; five single-target trials, five redundant-target trials, 15 single non-target trials, and 15 redundant non-target trials. This design was chosen to ensure that both stimulus categories (number vs letter) and both stimulus orientations (left vs right) were presented equally often. The order of blocks within the sets was pseudo-randomized between participants.

Each trial began with a black fixation cross subtending 1.4° of visual angle, which remained on the screen for a random interval of 350–700 ms. The fixation cross then disappeared and the experimental stimuli appeared. The array was presented for 1500 ms, and participants were able to respond until the array disappeared and was replaced by a brief blank screen.

## Results

### Response times

Response times below 100 ms were assumed to be anticipatory and were discarded. A 2 (trial type; single target vs redundant targets) × 5 (presentation type; central vs bilateral top vs bilateral bottom vs unilateral left vs unilateral right) within-subjects factorial ANOVA was conducted on RT. For the single-target trials, only the RT from the faster single-target location for each participant was employed, to minimize the possibility that any redundancy gain was due to spatial uncertainty in the single-target trials. Because a go/no-go paradigm was employed, only trials in which participants correctly responded to a target could be included in RT analyses: 1.40% of trials were excluded due to participants failing to respond to a target. Response times are illustrated in Figure 1.

The main effect of trial type was significant, $RT_{single} = 506$ ms, $RT_{redundant} = 526$ ms, $F(1, 14) = 9.01$, $p = .010$, partial $\eta^2 = .39$. Thus, instead of the expected redundancy gain, there was a redundancy loss compared to the faster single target location.

The main effect of presentation type was also significant, $F(4, 56) = 9.14$, $p < .001$, partial $\eta^2 = .395$. Bonferroni-corrected post-hoc tests with an alpha level of .005 indicated that participants responded more quickly to bilateral top presentation than to unilateral right presentation, and more quickly to bilateral bottom presentation than to central or unilateral right presentation, all $p$s $< .004$. There was a tendency for bilateral presentations to be faster than unilateral left presentations, but the tests did not reach significance, $p$s $> .007$. Thus, in general, there was a tendency for the bilateral presentations to be faster than central and unilateral presentations, as expected.

Finally, the interaction of trial type x presentation type was also significant, $F(4, 56) = 4.79$, $p = .002$, partial $\eta^2 = .25$. We conducted Bonferroni-corrected post-hoc tests of the simple effect of trial type with an alpha level of .01. These tests indicated that participants

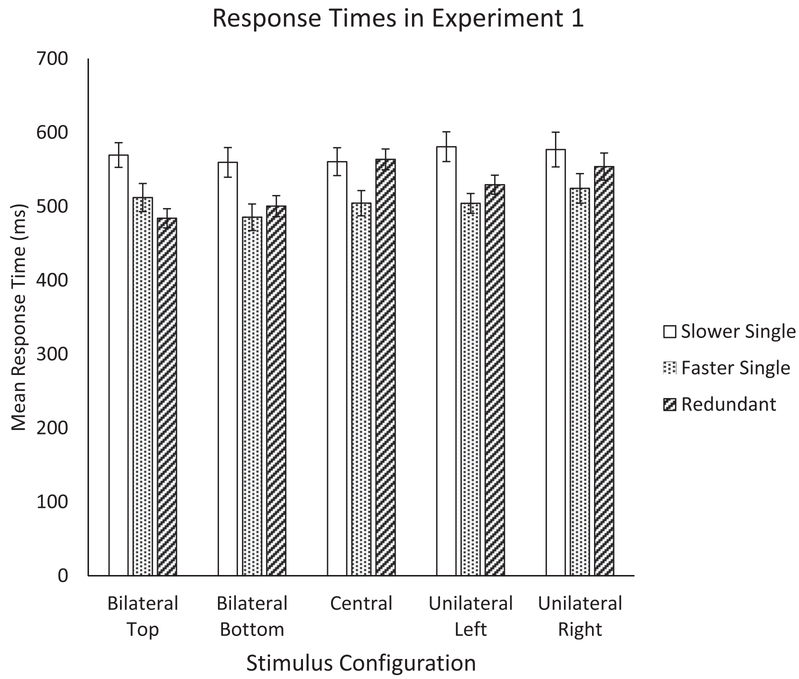


**Figure 1.** Mean response times as a function of trial type in Experiment 1. Error bars represent two within-subjects standard errors above and below the mean, calculated using the method outlined by Morey (2008).

only made significantly faster responses to single-target compared to redundant-target trials in the central presentation type, $p = .001$. In bilateral bottom and unilateral trials, the trend was not significant, all $ps > .039$. In bilateral top trials, the trend was towards a redundancy gain, but it was not significant; $p = .069$.

Because there was no redundancy gain evident in this experiment, the RT distributions were not tested for violations of the race model inequality.

Given that a race between two targets should only be possible if their response time distributions overlap, the percentage of overlap between the two single-target response time distributions was also calculated for each display configuration and for each participant. Percent overlap was calculated as the mean percentage of response times in each single-target location that fell between the minimum and maximum response times of the other single-target location. Percent overlap was then subjected to a one-way, five-level within-subjects ANOVA with display configuration as the independent variable. The effect of display configuration did not reach significance, $F(1,14) = 2.42$, $p = .059$, partial $\eta^2 = .15$.

### *Accuracy*

A 4 (trial type; single non-target vs redundant non-target vs single target vs redundant target) × 5 (presentation type) within-subjects factorial ANOVA was conducted on accuracy. The single-target accuracy was calculated for the faster single-target location for each participant. Mauchly's test indicated that sphericity was violated for both factors and the interaction, $p < .018$ for all; the Greenhouse-Geisser correction for degrees of freedom was employed for all variables. The main effects and the interaction effect were all non-significant, all $Fs < 1.95$, all $ps > .159$. Thus, the observed RT effects were not attributable to a speed–accuracy trade-off.

## *Discussion*

In Experiment 1, there was no significant redundancy gain for any display condition, whether bilateral, unilateral, or central. In fact, there was an overall redundancy loss, which was strong enough to be significant only in the central presentation trials. This difficulty in processing items on the vertical centre line of vision is consistent with previous research (Abrams et al., 2012; Carrasco et al., 2004; Corbett & Carrasco, 2011) and suggests that such a configuration is not ideal for the presentation of multiple items. Bilateral top trials may have had a slight trend towards a redundancy gain, although the trend was not significant.

Why did these results occur, when several previous researchers have found redundancy gain for categorization tasks? It is possible that previous researchers did not find a real categorical redundancy gain. As mentioned in the introduction, identical redundant stimuli could have allowed participants to rely on redundancy of basic visual features; participants in other studies could have benefited from noise reduction in redundant-target conditions, rather than benefiting from redundancy. Alternatively, Experiment 1 could have inhibited a redundant signals effect by changing participants' processing strategies. Most previous studies on the redundant signals effect have employed brief stimuli; for example, Reinholz and Pollman (2007) presented pictures of faces and buildings for 200 ms per display, whereas the current study used 1500 ms presentation times. Previous research has indicated that processing strategies can be changed by changing the duration of a visual stimulus (Hollands & Spence, 1998; Lagroix, Di Lolli, & Spalek, 2015). Perhaps the presence of a longer display duration allowed participants to recheck their conclusions about the presence or absence of a target, which would mask any redundancy gain present in the initial decision. Experiment 2 employed a stimulus duration of 100 ms to determine the effect of display configuration on the redundant signals effect for briefly-presented, categorically-defined stimuli.

## Experiment 2

### Method

#### Participants

Seventeen participants (15 female, mean age = 18.94) were recruited from the University of Central Florida Psychology Department subject pool and participated for partial course credit. One participant was excluded because the eye tracker could not be calibrated, and one participant chose not to complete the experiment; 15 participants were included in data analysis. All participants had normal or corrected-to-normal near visual acuity and colour vision.

#### Apparatus and stimuli

All stimuli and equipment were the same as in Experiment 1.

#### Procedure

The procedure was the same as for Experiment 1, with the exception of the display duration. The experimental stimuli were displayed for 100 ms, followed by a 1400 ms blank screen. Participants were able to respond for 1500 ms following the onset of the experimental stimuli. The trial ended after 1500 ms or after participants had made a response.

### Results

#### Response times

Response times below 100 ms were assumed to be anticipatory responses and were discarded. A 2 (trial type; single target vs redundant targets) x 5 (presentation type; central vs bilateral top vs bilateral bottom vs unilateral left vs unilateral right) within-subjects factorial ANOVA was conducted on RT. For the single-target trials, only the RT from the faster single-target location for each participant was employed. As with Experiment 1, only trials in which a response was made could be included in RT analyses: 0.45% of trials were excluded due to participants failing to respond to a target. Mean response times are illustrated in Figure 2.

The main effect of trial type was not significant, $RT_{single} = 454$ ms, $RT_{redundant} = 462$ ms, $F(1,14) = 3.19$, $p = .096$, partial $\eta^2 = .19$. Thus, there was no redundancy gain and no trend towards a redundancy gain. The main effect of presentation type was significant, $F(4,56) = 5.42$, $p = .001$, partial $\eta^2 = .28$. Bonferroni-corrected post-hoc tests with an alpha level of .005 indicated that participants responded more quickly to bilateral bottom presentations than to central or unilateral right presentations, $ps < .004$ for both. All other bilateral presentations tended to be faster than central or unilateral presentations, although the differences were not significant with the Bonferroni correction, $ps = .008$ to .045. Central and unilateral presentations did not differ from each other, all $ps > .473$. Thus, there was a trend towards bilateral presentations being faster than other types of presentations, although not all of the differences reached statistical significance.

Finally, the interaction of trial type x presentation type was significant, $F(4,56) = 7.19$, $p < .001$, partial $\eta^2 = .34$. Bonferroni-corrected post hoc tests of the simple effect of trial type with a corrected alpha level of .01 indicated that participants responded

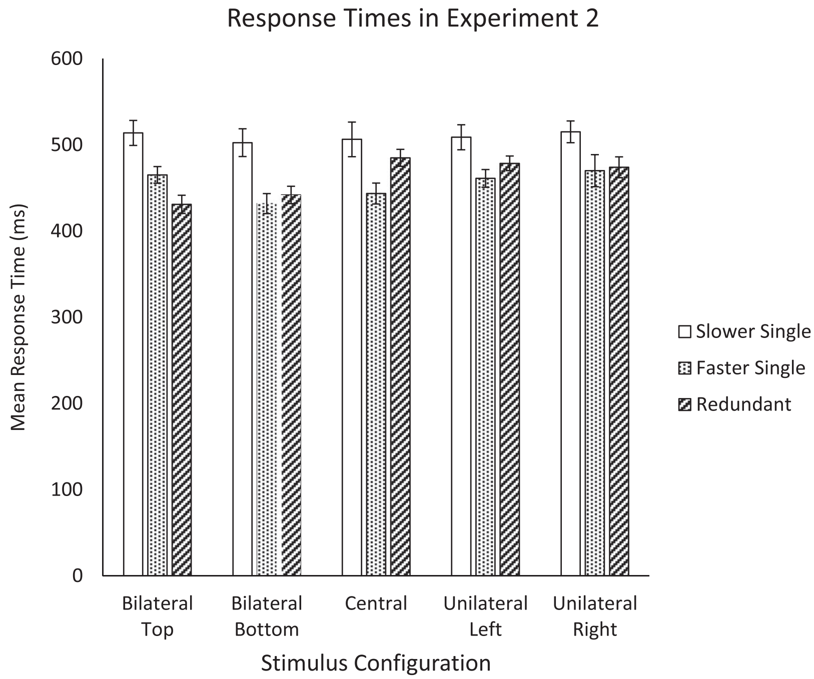


**Figure 2.** Mean response times as a function of trial type in Experiment 2. Error bars represent two within-subjects standard errors above and below the mean, calculated using the method outlined by Morey (2008).

significantly more quickly to redundant targets than to single targets in the bilateral top presentation type, $p < .001$. Participants were significantly slower in redundant- than in single-target trials in the central presentation type, $p = .002$. Single- and redundant-target trials did not significantly differ in any other presentation type, although there was a trend towards redundancy loss in unilateral left trials, $p = .043$ for unilateral left, *ps* > .312 for others. Given that participants responded with their right hand, this trend towards redundancy loss only for stimuli in the left visual field and not in the right visual field could reflect an interaction of stimulus-response compatibility with redundancy.

### *Race model inequality*

For the bilateral top presentation type, which showed a significant redundancy gain, we tested for violations of the race model inequality defined by Miller (1982):

$$P(\mathrm{RT} < t|\mathrm{AB}) \leq P(\mathrm{RT} < t|\mathrm{A}) + P(\mathrm{RT}|\mathrm{B}), \qquad (1)$$

where $P(\mathrm{RT} < t)$ refers to the probability that a response has occurred before time $t$, AB refers to the presence of two signals (the redundant-target condition), and A and B each refer to one single target; here, A is a single target in the upper left visual field, and B is a single target in the upper right visual field. If the redundant-targets RT distribution, $P$ (RT < $t$|AB) is anywhere to the left of the summed single-signal RT distributions, it suggests that the redundant-target responses can be faster than predicted by mere statistical facilitation. The RT distributions and the upper bound of the race model inequality were calculated according to the procedure outlined by Ulrich, Miller, and Schröter (2007), in which the RT associated with several quantiles is calculated for both the redundant-targets distribution and the sum of the single-target distributions. The RT associated with each quantile is then compared between the distributions to determine whether the redundant-targets distribution is significantly faster than the summed single-target distribution at any quantile. If so, it indicates a violation of the race model inequality, suggesting some form of coactive processing.

For the bilateral top presentation type, we conducted five paired-samples, one-way $t$-tests to compare the two distributions. RTs were tested at quantiles 0.1, 0.3, 0.5, 0.7, and 0.9. The redundant-target RT was nowhere significantly faster than the race model bound, *ps* > .544 for all quantiles; thus, a race model is sufficient to explain redundancy gain in the bilateral top presentation type.

The percentage of overlap between the two single-target response time distributions was also calculated for each display configuration and subjected to a one-way, five-level, within-subjects ANOVA with display configuration as the independent variable. There was a significant effect of display configuration, $F(4, 56) = 3.88$, $p = .008$, partial $\eta^2 = .22$. Bonferroni-corrected post-hoc tests with an alpha level of .005 indicated that bilateral bottom targets had significantly lower response time overlap than bilateral top displays, $p = .001$, and unilateral right displays, $p = .0048$. No other significant differences occurred between display configurations, $p > .091$ for all. The fact that bilateral top displays only differed from bilateral bottom displays, but not from any other configuration, $p > .161$ for all, may suggest that the amount of overlap was not responsible for the significant redundancy gain for bilateral top displays. Additionally, the fact that central display configuration did not significantly differ from any other display configuration, $p > .106$ for all, may indicate that the amount of overlap was also not responsible for redundancy loss in central displays.

### *Accuracy*

A 4 (trial type) × 5 (presentation type) within-subjects factorial ANOVA was conducted on accuracy. The single-target accuracy was calculated from the faster single-target location for each participant. The Greenhouse-Geisser correction for degrees of freedom is reported where sphericity was violated.

The main effect of trial type was significant, $F(3, 42) = 10.12$, $p < .001$, partial $\eta^2 = .42$. Bonferroni-corrected post-hoc tests with an alpha level of .008 indicated that the non-target trials were significantly less accurate than the target-present trials, $ps < .006$, with the exception of double non-target vs single-target trials, where the trend was not significant, $p = .019$. Non-target trials did not differ from each other, and single-target trials did not differ from redundant-target trials, $ps > .129$ for all. Thus, the main effect of trial type was due to differences between target-absent and target-present trials, and not due to differences between single- and redundant-target trials.

The main effect of presentation type was not significant, $F(2.26, 31.61) = 1.02$, $p = .380$, partial $\eta^2 = .07$. The interaction of target type × presentation type was also not significant, $F(12, 168) = 0.98$, $p = .472$, partial $\eta^2 = .07$. There is therefore no evidence that the redundancy gains and losses in RT are attributable speed–accuracy trade-offs.

## General discussion

The current study was designed to test the hypotheses that redundancy gain in categorical processing is possible, that it depends on bilateral presentation, and that a race model will suffice to explain the effect. The results partially supported these hypotheses. When the stimuli were displayed for as long as the participants needed to make a response (Experiment 1), RT to redundant-target trials was not significantly faster than single-target trials in any display configuration, although there was a marginally significant trend when stimuli were displayed bilaterally in the upper visual field. When stimuli were displayed along the vertical centre line of vision, there was a significant redundancy loss, such that RT was slower to redundant- than to single-target trials. However, a significant bilateral redundancy gain, for the upper visual field only, emerged when stimuli were only presented for 100 ms (Experiment 2). Participants did not violate the race model inequality in this condition, indicating that a race model was sufficient to explain the effect. No other display configurations had a significant redundancy gain, and the central configuration again showed a significant redundancy loss. It thus appears that, for the upper visual field, non-identical bilateral targets can enhance processing speed in a categorization task, at least when stimulus presentation is brief. It is worth noting, however, that there was a non-significant trend towards redundancy gain for long-lasting bilateral top displays, suggesting that there might be a weak benefit of bilateral redundancy even for longer stimulus durations. Processing of other display configurations does not seem to benefit from redundancy, and may even be impaired by it. Finally, both bilateral configurations enabled significantly faster responses than unilateral and central configurations.

The results of the current study are consistent with those of previous studies that have found bilateral redundancy gain for categorization or similar semantic processing tasks (e.g., Hasbrooke & Chiarello, 1998; Marks & Hellige, 2003; Mohr et al., 1996, 1994, 2007; Reinholz & Pollman, 2007). Importantly, the current study shows evidence that a bilateral redundancy gain can occur without standard stimuli or previous target categories being used in the single-target conditions, suggesting that it is not merely an effect of slowing in the single-target conditions due to increased load on a severely limited-capacity processing system. Additionally, because the stimuli were never identical, the redundancy gain was not attributable to redundancy of identical visual stimuli, but instead was attributable to redundancy of category membership. However, the fact that accuracy was higher for target-present than for target-absent trials could introduce a further limit to when redundancy will occur. High accuracy for "go" trials and relatively lower accuracy for "no-go" trials both indicate a bias towards making a "go" response. In situations in which participants are already biased for a "go" response, then the presence of a second "go" signal might not significantly increase speed if the first "go" signal is strong enough. Thus, a biased responder combined with a strong signal could eliminate redundancy gain.

The current finding of a redundancy gain in some bilateral displays, and not unilateral or central displays, is consistent with some previous research finding that redundancy gain is enhanced for bilateral compared to unilateral presentations (Girard et al., 2013; Schulte et al., 2004). It is also consistent with research showing a more nuanced relationship between bilateral and unilateral redundancy; Banich and Karol (1992) asked participants to decide whether at least one word in a display rhymed with a probe word. When two identical words were displayed, unilateral configurations were faster than bilateral configurations; but when two different words were displayed, unilateral configurations were slower than bilateral configurations. In the current study, redundant-target trials required participants to determine the category membership of two stimuli that always differed from each other; Banich and Karol's results would indicate that interhemispheric processing would be advantageous in this case. Additionally, Patel and Hellige (2007) found that matching targets or target categories displayed in a similar format (e.g., matching numerals to numerals) is more difficult when the items are displayed unilaterally than when the items are displayed bilaterally. By contrast, matching target categories in a different format (matching numerals to dot patterns) is more difficult when the items are displayed bilaterally than when they are displayed unilaterally. They suggested that this is because processing of similar-format items, when presented to the same hemifield, necessitates processing both stimuli within highly overlapping neural areas, leading to interference between the two stimuli; processing different-format items causes less neural interference, and the advantage of not needing to compare items across hemispheres therefore outweighs any interference between the items. In the current study, participants were required to process two similar-format items; unilateral presentation might therefore cause enough interference between targets to outweigh the advantage of redundancy, whereas less interference occurs between bilateral targets.

The same necessity to process two similar-format items in one hemifield could explain why there was a significant redundancy loss when stimuli were presented along the vertical centre line of vision. As Abrams et al. (2012) suggested, the North effect (difficulty processing stimuli on the vertical meridian) may be due to the presence of half of each stimulus in one visual hemifield and half in the other, necessitating crosstalk between the two hemispheres simply to understand a single stimulus. Add to that the interference between two similar stimuli that occurs within one hemisphere, and redundant signals in a central presentation format should be especially difficult to process. This effect may explain why Grice and colleagues found that the redundant signals effect for non-categorical targets was mostly or entirely due to noise reduction (Grice et al., 1984; Grice & Canham, 1990; Grice & Gwynne, 1987; Grice & Reed, 1992), given that they also presented targets along the vertical meridian of vision.

One interesting finding is that only bilateral top configurations showed a redundancy gain; bilateral bottom configurations had no evidence of a redundancy gain in either experiment. Previous research that has demonstrated a difference between upper and lower visual fields has found the opposite effect, such that redundancy gain occurred in the lower visual field and not in the upper visual field or was greater for the lower than for the upper field (de Gelder, Pourtois, van Raamsdonk, Vroomen, & Weiskrantz, 2001) and that this effect is paralleled by latencies in early ERP components (Miniussi et al., 1998). It is unclear why this disparity would occur when all three studies required participants to begin a trial with their eyes on a central fixation cross; perhaps the fact that the current stimuli were numbers and letters, and that text is usually arranged such that upper text is meant to be read before lower text, affected how participants attended to different portions of the screen in the current study. Regardless, this study combined with the previous studies suggests that even bilateral redundancy gain may depend on limiting bilateral presentation to certain portions of the visual field.

The results also suggest that a race model, in which the target that is processed more quickly is the one that triggers a response, is sufficient to explain the bilateral redundancy gain. This is consistent with some of the previous research, which finds that race models can explain redundancy gain when the redundant signals are presented in two separate objects (Akyürek & Schubö, 2013; Feintuch & Cohen, 2002; Mordkoff & Danek, 2011). Further possibilities are that bilateral stimuli are processed coactively but interhemispheric inhibition slows down processing times enough to prevent violation of the race model inequality (Barr & Corballis, 2003; Corballis, Hamm, Barnett, & Corballis, 2002) or that some level of interhemispheric coactivation can occur even if only a single stimulus is presented unilaterally (Corballis, 1998). However, some research with simple RT tasks has found coactivation for bilateral stimuli in healthy participants (e.g., Miniussi et al., 1998; Savazzi & Marzi, 2008). It is possible that bilateral stimuli need to be visually identical or nearly identical to allow interhemispheric coactivation to occur or to avoid interhemispheric inhibition; future research could determine if this is the case.

A further possibility is that the addition of orientation discriminations to the target detection task discouraged coactive processing of both targets by requiring a conjunction of two decisions for each target, i.e., whether an object was a digit, and whether an object was tilted to the left. Given that two perceptually separable target dimensions do not necessarily force participants to make two separate decisions (Ashby & Maddox, 1990), it is possible that participants did not need to monitor orientation and category separately; however, Ashby and Maddox employed size-plus-orientation decisions with no higher-level semantic categories involved, and further research may be needed without conjunction targets to determine whether a race model holds true in purely semantic category decisions.

Future research with larger, less well-practiced categories is also warranted. Single digits and letters are small categories with which participants have extensive familiarity. It is possible that participants treated these categories as sets of exemplars, making the current study a study on redundancy in uncertain, but specific, targets rather than categorical targets.

Given that category recognition may be accomplished preattentively by applying templates of simple category-defining features (Zelinsky, Peng, Berg, & Samaras, 2013), it is also possible that categorical redundancy gain is accomplished through the redundant presence of features belonging to those templates. This would place categorical redundancy gain at an early stage of visual processing; research with larger and less well-defined categories could manipulate the presence or absence of simple, category-typical features to determine whether categorical redundancy gain is accomplished during the processing of simple visual features.

Additionally, we did not explicitly test how stimulus duration affects processing strategies. As a result, we cannot come to any firm conclusion about why long-lasting displays seem to weaken redundancy gain. Future research in which different processing strategies are encouraged could clarify whether redundancy gain occurs even when participants are rechecking stimuli. On a final note, a non-significant redundancy loss in left visual field stimuli, but not the right visual field, for brief stimuli may indicate that redundancy effects are dependent on stimulus-response compatibility. Future research exploring the effect of stimulus-response mappings could clarify this effect.

Regardless, it appears that redundancy gain can occur for non-identical stimuli in a categorization task, at least in some bilateral configurations. Given that redundancy gain only occurred for bilateral configurations, it is possible that interhemispheric interaction is an important component of redundancy gain for such targets. However, categorical target redundancy can also be harmful when targets are arranged vertically in the centre of vision. Categorical redundancy gain therefore appears to be possible, but dependent on the targets' locations within the visual field.

## Note

1. Prior to the study, two pilot studies were conducted with stimuli presented for 100 ms to the left and right of centre. In one study, 17 participants responded to the presence of teddy bears (categorical decisions); in the

other, 16 participants responded to the presence of the letter "N" (non-categorical decisions). Each study contained 160 trials evenly split between no-target, single-left, single-right, and redundant-target trials. Both studies exhibited significant redundancy gain ($p < .013$ for both), indicating that a small number of participants and a small number of trials are sufficient to detect redundant gain.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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