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Size congruity influences visual search via the target template

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A B S T R A C T

In numerical comparison experiments, participants are presented with two digits that vary in numerical and physical size, and they select the numerically (or physically) larger (or smaller) of the two digits. Response times are typically faster when numerical and physical size are congruent than when they are incongruent, which is called the size congruity effect (SCE). Although numerical size is unlikely to be a guiding feature in visual search, recent studies have nevertheless observed the SCE in the visual search paradigm. To explain this puzzling fact, we hypothesized that the incongruity between a target's numerical and physical size affects visual search primarily when an attended item is compared to the target template in visual short-term memory. In three experiments, participants searched for a target whose numerical and physical size were distinct from non-target distractors. The SCE and shallow search slopes in Experiment 1 suggest that the target's physical size captured attention, and only then did incongruent numerical size interfere with the response. Instructing participants to attend to physical size in Experiment 2 abolished the SCE, suggesting that participants did not analyze the target's numerical size when they could be confident that physical size was a reliable target cue. Presenting each of two possible target digits in blocks as in Experiment 3 enabled participants to load the visual features of shape and physical size into their target template, and once again the SCE was abolished. The three experiments show that the SCE in visual search can be reduced or eliminated by restricting the target template based on specific physical features and thus discouraging participants from analyzing the target's numerical size.

1. Introduction

In traditional numerical comparison tasks (Moyer & Landauer, 1967), participants select one of two digits based on its numerical size. Besner and Coltheart (1979) extended this technique by varying the digits' physical size so numerical and physical size could be either congruent (e.g., 2 and **9**) or incongruent (e.g., **2** and 9). In such a task, selecting the numerically (or physically) larger (or smaller) digit is generally faster when the numerical and physical size are congruent than when incongruent (Besner & Coltheart, 1979; Henik & Tzelgov, 1982). This result, called the size congruity effect (SCE), implies that a numeral's semantic (numerical size) and perceptual (physical size) characteristics interact mentally in a manner reminiscent of the classic Stroop (1935) effect.

2. Stroop and reverse Stroop effects in identification and localization

In one of Stroop's (1935) experiments, participants viewed either color words written in ink that was incongruent with the meaning of the word, or colored blocks. Naming the color of the ink was slower for incongruent color words than colored blocks, which has become known as the Stroop effect. Much less well known than the color naming experiment was one in which participants read the words aloud (MacLeod, 1991). In this experiment, word reading was no slower for color words written in an incongruent color ink than color words written in a neutral (i.e., black) ink. In a third experiment, Stroop showed that incongruent ink color *can* interfere with word reading, but only after several days practicing ink color naming, and this effect promptly vanished in a follow-up task. Although Stroop found interactions between a word's meaning and ink color in both color naming and word reading tasks, the first has become known as the Stroop effect and the second as the reverse Stroop effect.

The likely reason for this naming convention is that the Stroop effect is so much more robust than the reverse Stroop effect. Indeed, whereas MacLeod (1991) reviewed hundreds of articles replicating the Stroop effect, replications of the reverse Stroop effect are comparatively rare (Blais & Besner, 2006). This asymmetry between the Stroop and reverse Stroop effects has traditionally been explained as the result of automaticity (Besner, Stolz, & Boutilier, 1997; Blais, Harris, Guerrero, &

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Bunge, 2012). That is, participants are presumed to have had much more experience reading words than naming colors, so incongruent word meaning interferes with ink color naming (Stroop) more than the other way around (reverse Stroop).

Whereas the automaticity account implies a special status for word reading, many studies replicating the reverse Stroop effect (e.g., Virzi & Egeth, 1985) have argued that Stroop interference results from the need to translate mental codes between the stimulus and response. Because identification of either the target's color (Stroop) or meaning (reverse Stroop) entails a verbal response, a visual stimulus (ink color) needs to be translated into a verbal code in Stroop tasks, but a verbal stimulus (word meaning) requires no such translation in reverse Stroop tasks. The translation account implies that tasks eliciting a visual response should invert the traditional asymmetry such that the Stroop effect should be smaller than the reverse Stroop effect. To support this claim, Durgin (2000; and a recent replication by Miller, Kubicki, Caffier, Kolski, & Naveteur, 2016) presented color words that appeared in a visual color, and instructed participants to localize one of four color patches that matched either the cue's color (Stroop) or meaning (reverse Stroop). The Stroop task required no translation between the cue's color and the matching color patch, but the reverse Stroop task *did* require the cue's meaning be translated into a visual code to match the corresponding color patch. Consistent with the translation account, the Stroop effect was smaller than the reverse Stroop effect.

Blais and Besner (2007) argued that a localization task such as the one used by Durgin (2000) should have been sufficient to elicit a reverse Stroop effect even without any need for translation. That is, localization tasks are more strongly associated with perceptual processing than semantic processing, so attending to the target's semantic feature (word meaning) in a localization task should elicit more interference than attending to its perceptual feature (color). In contrast, the traditional Stroop task is identification, which is more strongly associated with semantic processing. According to the strength-of-association account, this is why attending to the target's perceptual feature (color) in traditional Stroop tasks elicits more interference than attending to the target's semantic feature (word meaning) in reverse Stroop tasks. Blais and Besner (and a recent replication by Yamamoto, Incera, & McLennan, 2016) adapted Durgin's task by replacing the color patches with color words so no translation was required between the meaning of the cue and the meaning of the matching color word. Consistent with the strength-of-association account, they observed a reverse Stroop effect even though no translation was required.

Sobel, Puri, and Faulkenberry (2016) recently extended the size congruity paradigm to a visual search localization task (as Blais and Besner (2007) did for Stroop). This study included both a reverse Stroop task, in which participants localized the item with a unique numerical (semantic) size (Experiment 1), and a Stroop task in which they localized the item with a unique physical (perceptual) size (Experiment 2). In both experiments, every display contained one item that was both numerically and physically unique; the only difference between experiments was that participants were instructed to attend to numerical size in Experiment 1 and physical size in Experiment 2. In both experiments, RTs were faster for congruent targets than incongruent targets, but this SCE was significantly greater in Experiment 1 (reverse Stroop) than Experiment 2 (Stroop). Experiments 4 and 5 were also analogous to a reverse Stroop and Stroop task, respectively, but targets and distractors were three-digit numerals. Because salience of visual features increases with display density (Bravo & Nakayama, 1992; Sobel, Pickard, & Acklin, 2009; Todd & Kramer, 1994), packing more items into the same size display was intended to boost the salience of the target's physical size, thereby reducing the role of numerical size. As expected, the significant SCE in Experiment 4 (reverse Stroop) was not just reduced, but completely abolished, in Experiment 5 (Stroop).

3. The presence of the SCE in visual search is surprising

A larger SCE when participants attended to a target's numerical size rather than its physical size accords well with the strength-of-association prediction that reverse Stroop should be larger than Stroop effects for localization tasks, and yet the mere presence of the SCE in visual search is somewhat surprising. One obstacle to observing the SCE in visual search is that manipulating a search item's semantic associations typically also entails manipulating its shape (e.g., 9 is numerically larger than 2, but also has a different shape), so it is difficult to disentangle the effect of numerical size from the effect of shape (Krueger, 1984; Wolfe & Horowitz, 2004). Nevertheless, researchers have recently developed an assortment of techniques to control for an alphanumeric character's shape in visual search, enabling them to reveal the influence of the character's meaning on visual search (Godwin, Hout, & Menneer, 2014; Krause, Bekkering, Pratt, & Lindemann, 2017; Lupyan, 2008; Lupyan & Spivey, 2008; Schwarz & Eiselt, 2012; Sobel, Puri, & Hogan, 2015).

Whereas these studies tamed the confound between a target character's shape and meaning, a second obstacle to observing the SCE in visual search concerns the dubious status of numerical size as a guiding feature in visual search (Sobel, Puri, Faulkenberry, & Dague, 2017). A guiding feature is defined by its ability to limit the range of items through which search proceeds (Wolfe & Horowitz, 2004). If numerical size is not a guiding feature, how does it exert any influence on visual search? We believe that the target first captures attention due to its unique physical size (undoubtedly a guiding feature according to Wolfe & Horowitz), then, only after attention is directed to the physical size singleton, does its numerical size have the opportunity to interfere with the participant's decision to report that the attended item is the target. This echoes Risko, Maloney, and Fugelsang (2013), who argued that in traditional size congruity experiments with just two numbers to compare, one number captures attention, and only then does incongruent numerical size interfere with the participant's decision. However, Arend and Henik (2015) identified two methodological limitations that they claimed undermined the validity of Risko et al.'s conclusions: participants selected the numerically larger item, but were never asked to select the numerically smaller item, nor were they ever asked to attend to the items' physical size. To extend on Risko et al. while seeking to overcome the methodological limitations identified by Arend and Henik, in our experiments we included four conditions: participants searched for the numerically small, numerically large, physically small, and physically large item.

4. The role of the target template

Our attentional-capture-then-interference model of the SCE in visual search relies heavily on the role of the target template in visual short-term memory (VSTM). When participants search for a single item of interest from among several non-target distractors, they maintain a target template in VSTM for comparison with target candidates (Beck, Hollingworth, & Luck, 2011; Olivers, Peters, Houtkamp, & Roelfsema, 2011). The precision of the target template affects both attentional guidance and decision-making (Hout & Goldinger, 2015).

As a first step to probe the influence of the target template on the SCE in visual search, we noted that in our previous study when participants were instructed to search for the digit with a unique numerical size (Sobel et al., 2016, Experiment 1), the target's physical size varied randomly across trials. Because of this inter-trial interference, participants were prevented from developing a template that specified the target's physical size. What if each participant were exposed to exclusively congruent or incongruent targets?

It is well known that the Stroop effect is sensitive to the ratio of the frequency of congruent and incongruent trials (Blais et al., 2012; Jiménez & Méndez, 2013), but in our experiments we wanted to see if presenting exclusively congruent or incongruent targets would