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Visual Search for Conjunctions of Physical and Numerical Size Shows That They Are Processed Independently

Kenith V. Sobel
University of Central Arkansas

Amrita M. Puri
Illinois State University

Thomas J. Faulkenberry
Tarleton State University

Taylor D. Dague
University of Central Arkansas

The size congruity effect refers to the interaction between numerical magnitude and physical digit size in a symbolic comparison task. Though this effect is well established in the typical 2-item scenario, the mechanisms at the root of the interference remain unclear. Two competing explanations have emerged in the literature: an early interaction model and a late interaction model. In the present study, we used visual conjunction search to test competing predictions from these 2 models. Participants searched for targets that were defined by a conjunction of physical and numerical size. Some distractors shared the target's physical size, and the remaining distractors shared the target's numerical size. We held the total number of search items fixed and manipulated the ratio of the 2 distractor set sizes. The results from 3 experiments converge on the conclusion that numerical magnitude is not a guiding feature for visual search, and that physical and numerical magnitude are processed independently, which supports a late interaction model of the size congruity effect.

Public Significance Statement

People can process numerical quantities more quickly when a digit's physical (i.e., font) and numerical size are congruent (e.g., "2" written in a small font and "9" written in a large font) than when they are incongruent (e.g., "2" written in a large font and "9" written in a small font). Does this interaction between digits' physical and numerical sizes occur because the two kinds of size are mentally processed together? To find out, we used visual search, a task that is presumed to be driven by perceptual processing. Visual search was affected primarily by digits' physical sizes but not their numerical sizes. Even though the processing of digits is affected by the congruence between physical and numerical size, this study showed that the mental processing of physical and numerical size is nevertheless separate.

Keywords: size congruity, conjunction search, distractor ratio effect, early versus late interaction

To successfully navigate the world, people need to effectively perceive and understand spatial, temporal, and numerical magnitudes (Winter, Marghetis, & Matlock, 2015). Cross-domain interactions abound in everyday experience, such as the interaction between space and time that occurs when the question "How far is Memphis?" elicits the response "About four hours away" (Casasanto & Boroditsky, 2008). The interaction between spatial and numerical size of digits has been well documented in the size congruity effect (Besner & Coltheart, 1979; Henik & Tzelgov, 1982). In a typical size congruity experiment, participants are presented with two numbers that have different physical and numerical sizes, and they select the item with the larger (or smaller) physical (or numerical) size. One dimension is task-relevant and the other irrelevant, so, for example, when selecting the physically larger item, only the numbers' physical sizes are relevant to the task. Nevertheless, response times are generally faster when physical and numerical size are congruent (i.e., the physically larger item is also numerically larger than the other item) than when incongruent.

Although the size congruity effect is widely interpreted as evidence that physical and numerical size interact, disagreement remains about the locus at which the interaction occurs (Arend & Henik, 2015; Santens & Verguts, 2011). According to the early interaction model (Schwarz & Heinze, 1998; Walsh, 2003), physical and numerical size are initially mapped onto a single mental

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Kenith V. Sobel, Department of Psychology and Counseling, University of Central Arkansas; Amrita M. Puri, Department of Psychology, Illinois State University; Thomas J. Faulkenberry, Department of Psychological Sciences, Tarleton State University; Taylor D. Dague, Department of Psychology and Counseling, University of Central Arkansas.

Correspondence concerning this article should be addressed to Kenith V. Sobel, Department of Psychology and Counseling, University of Central Arkansas, 201 Donaghey Avenue, Mashburn Hall 260, Conway, AR 72035. E-mail: k.sobel@mac.com

representation, and remain integrated throughout the entire processing sequence. In contrast, the late interaction model (Faulkenberry, Cruise, Lavro, & Shaki, 2016; Santens & Verguts, 2011) asserts that physical and numerical size occupy two distinct mental representations that proceed through separate, parallel processing sequences and only interact at a later decision stage. In the present study, we used visual search to test predictions made by the early and late interaction models.

Visual search is a widely used method for investigating how visual attention distinguishes a target item from among several nontarget distractors. After Risko, Maloney, and Fugelsang (2013) revealed that attention can influence the size congruity effect, the logical next step was to adapt the size congruity paradigm to visual search. Such experiments have confirmed that the size congruity effect extends to visual search: Specifically, a target is located faster when its physical and numerical size are congruent than when they are incongruent (Krause, Bekkering, Pratt, & Lindemann, 2016; Sobel, Puri, & Faulkenberry, 2016). In these studies, the target had a unique physical size in all displays, so participants could locate the target by attending to just a single dimension. If, instead, the target had neither a unique physical size nor numerical size, but could only have been distinguished from distractors by a unique *conjunction* of physical and numerical size, participants would have needed to attend to both dimensions.

In traditional conjunction search experiments (reviewed in Wolfe, 1998), a target is defined by a combination of two visual features (e.g., a line segment that is red and horizontal), among several distractors, half of which share one of the target's features (e.g., red verticals) and the remaining half share the other target feature (e.g., green horizontals). Display size is manipulated by adding equal numbers of both distractor types. As a result, the overall display size is confounded with the size of each distractor subset, so there is no way to discern whether search proceeds through the entire display or instead is limited to just one of the distractor subsets (Egeth, Virzi, & Garbart, 1984).

A common method for eliminating this confound is to hold the overall display size constant and manipulate the ratio of one distractor's set size to the other distractor's set size (Anderson, Heinke, & Humphreys, 2012; Bacon & Egeth, 1997; Elahipanah, Christensen, & Reingold, 2011; Poisson & Wilkinson, 1992; Shen, Reingold, & Pomplun, 2000; Sobel & Cave, 2002; Zohary & Hochstein, 1989). For example, if the overall distractor set size were fixed at 12 items, some displays would contain two target-color distractors and 10 target-orientation distractors, some would contain six of each, and some would contain 10 target-color distractors and two target-orientation distractors. For a target defined by a conjunction of color and orientation, search is more efficient when either distractor set is small than when the distractor set sizes are balanced, implying that search proceeds through whichever distractor set happens to be smaller (Poisson & Wilkinson, 1992; Zohary & Hochstein, 1989). It is not clear whether this pattern of behavior extends to visual search for a conjunction of physical and numerical size.

In the present study, we defined the target by a conjunction of physical and numerical size, so manipulating distractor ratio should reveal the nature of participants' representations of physical and numerical size as they search for the target. For all search displays in our experiments, the target's physical and numerical size were congruent and all distractors' physical and numerical sizes were incongruent. An example display might have contained a physically small "2" target among physically small "8"s and "9"s and physically large "2"s and "3"s, as depicted in Figure 1. All displays contained one target and 12 distractors, and we manipulated the ratio of the number of distractors that shared the target's physical size to the number of distractors that shared the target's numerical size.

For Experiment 1, we hypothesized three possible patterns of response time as a function of distractor ratio, which are depicted in Figure 2. If physical and numerical size are initially mapped onto a single mental representation as in the early interaction model, every distractor's representation should contain the fusion of its physical size and numerical size. Because the late selection model, but not the early selection model in Schwarz and Heinze (1998) includes components that *selectively* modulate the signal strength in the numerical and physical size channels, attention can be selectively deployed to one or the other of these features in the late selection model but not the early selection model. As a result, the early selection model implies that reaction time (RT) should be insensitive to manipulations of distractor ratio, as in the left panel of Figure 2. If, instead, physical and numerical size remain segregated from each other until a later decision stage, as in the late interaction model, attention can be flexibly deployed to either physical size or numerical size. The flexible deployment of attention entails two possible outcomes, depending on whether numerical size can guide search. For distractor ratio conjunction searches, a guiding feature elicits bottom-up attention when the items with that feature constitute the smaller of two groups (Poisson & Wilkinson, 1992; Sobel & Cave, 2002). Because an item's bottom-up salience is proportional to the difference between its own features and the features of adjacent items (Michael & Gálvez-García, 2011), each item with an uncommon feature will tend to be distinct from more of its neighbors than each item with a common feature, and thus be more salient. As a result, RTs are faster when the group with a guiding feature is small than when the group sizes are equal. According to Wolfe and Horowitz (2004), physical size is a guiding feature, so search can be restricted to the items that have the target's physical size when that set is smaller. The results from recent studies in which numerical magnitude influences search efficiency (Schwarz & Eiselt, 2012; Sobel, Puri, & Hogan, 2015) and eye fixations (Godwin, Hout, & Menneer, 2014) suggest that numerical size may also be a guiding feature. If both physical and numerical size are guiding features, search can be restricted to the items that have the target's physical size when that set is smaller, and to the items that have the target's numerical size when that set is smaller, yielding RTs that describe an inverted-V function of distractor ratio, as in the middle panel of Figure 2. On the other hand, Wolfe and Horowitz (2004) doubt that semantic associations such as numerical magnitude can guide search. If they are correct, search can be restricted to the items with the target's physical size, but not the items with the target's numerical size, yielding RTs that increase monotonically with distractor ratio, as in the right panel of Figure 2.

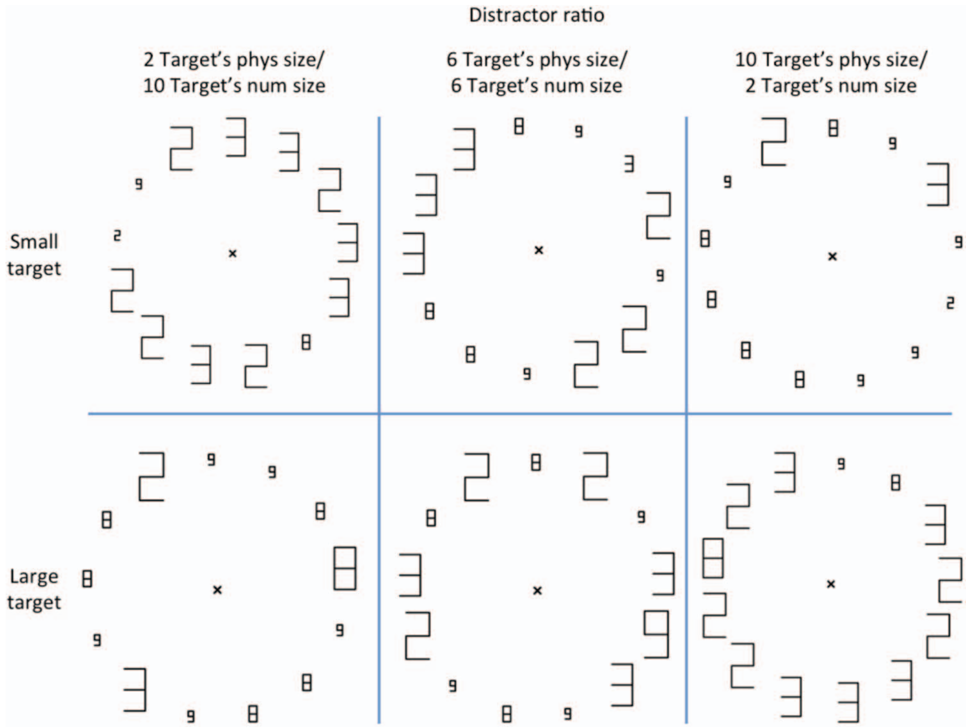

Figure 1. Screenshots of visual displays in Experiments 1 and 2. The target was physically and numerically small in one block, and physically and numerically large in the other block. The three distractor ratios represent the number of distractors that share the target's physical size divided by the number of distractors that share the target's numerical size. See the online article for the color version of this figure.

Experiment 1: Conjunctions of Physical and Numerical Size

Method

Participants. We obtained permission from the University of Central Arkansas (UCA) Institutional Review Board to carry out all three experiments, and treated participants in accordance with the ethical guidelines stipulated by the American Psychological Association (2010). In light of recent studies that have revealed a size congruity effect in visual search (Krause et al., 2016; Sobel et al., 2016), we anticipated a similarly large effect of d = 1.25, for which a minimum of 14 participants would be needed to achieve 80% power at an alpha of 0.05 (Bausell & Li, 2002). A total of 14 UCA undergraduate students (10 female, four male) between the ages of 19 and 26 years (M = 21.0) volunteered for the experiment in exchange for course credit.

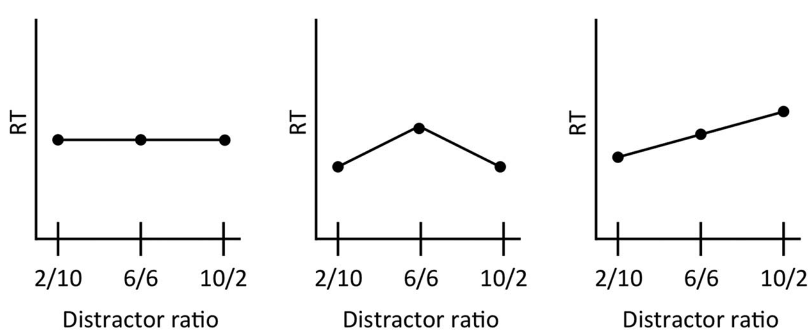

Figure 2. Hypothesized patterns of response time as a function of distractor ratio. For the three ratios along the *x*-axis, the numerator represents the set size of distractors that share the target's physical size, and the denominator represents the set size of distractors that share the target's numerical size. The flat function in the left panel would result if physical and numerical size were mapped onto a shared mental representation. The inverted-V function in the middle panel would result if search were restricted to whichever feature-defined set of items was smaller. The monotonically increasing linear function in the right panel would result if search were restricted to the set of items that has the target's physical size.

Apparatus. All three experiments were conducted on a MacBook computer connected to a CRT monitor with a screen resolution of 1024 × 768 pixels. Programs written in Xojo Basic presented stimulus arrays to the monitor and gathered responses from the keyboard.

Stimuli. In order to reduce shape differences between digits, we constructed versions of the Digits 2, 3, 8, and 9 from line segments as on the faces of digital clocks and depicted in the screen shots in Figure 1. All four digits appeared in every display. Each display contained one target digit and 12 distractor digits.

Pansky and Algom (1999) noted that size congruity experiments commonly employ several numerical sizes but just two arbitrarily selected physical sizes. They argued that (1) the overabundance of numerical sizes, and (2) physical size differences that are more salient than numerical size differences interfere with the processing of numerical size. We carefully designed our search items to avoid this interference. First, we used just as many physical sizes as numerical sizes: The numerals 2, 3, 8, and 9 had four different physical sizes. Second, to balance physical size differences with numerical size differences, the targets' physical sizes were proportional to their numerical sizes: the physical size of the 3 was 1.5 times larger than the physical size of the 2, the 8 was 4 times larger than the 2, and the 9 was 4.5 times larger than the 2. At a viewing distance of 56 cm, the Target Digit 2 was 0.34° wide × 0.68° tall, the Target Digit 3 was 0.51° wide × 1.02° tall, the Target Digit 8 was 1.36° wide × 2.72° tall, and the Target Digit 9 was 1.53° wide × 3.06° tall. The distractors' physical and numerical sizes were incongruent: Physically small distractors were numerically large and physically large distractors were numerically small. The physical sizes of the Digits 2 and 9 were switched so the Distractor Digit 2 was the same physical size as the Target Digit 9, and the Distractor Digit 9 was the same physical size as the Target Digit 2; the physical sizes of the Digits 3 and 8 were switched so the Distractor Digit 3 was the same physical size as the Target Digit 8, and the Distractor Digit 8 was the same physical size as the Target Digit 3.

In each display the search items (one target digit and 12 distractor digits) were distributed evenly around an imaginary circle with a radius of 8.0° that was centered on a fixation cross consisting of two orthogonal line segments each 1.0° long. The fixation cross and digits were white against a black background. The target digit appeared in one of four quadrant locations: upper right, lower right, lower left, or upper left. The participants' task in each trial was to indicate which side of the display contained the target. To ensure that the position of the target was readily distinguishable from the vertical meridian, targets were always placed at least 30° of arc away from vertical; that is, in terms of a clock face, targets in the upper right quadrant appeared in a randomly determined location between 1 o'clock and 3 o'clock, in the lower right quadrant between 3 o'clock and 5 o'clock, in the lower left quadrant between 7 o'clock and 9 o'clock, and in the upper left quadrant between 9 o'clock and 11 o'clock.

The ratio of the two distractor set sizes varied across trials. One third of displays contained two distractors that shared the target's physical size and 10 distractors that shared the target's numerical size, another third contained six of each distractor type, and the final third contained 10 distractors that shared the target's physical size and two distractors that shared the target's numerical size.

Procedure. The experiment began by presenting a series of instructional windows that participants could read at their own pace then click a button labeled "Next" to advance to the next window. Participants were informed they would be searching for a physically small number less than 5 in one half of the experiment, and a physically large number greater than 5 in the other half of the experiment; block order was counterbalanced across participants.

Each trial began with the onset of the stimulus array, which remained visible until participants responded by pressing either "z" to report that the target appeared on the left side of the display or "/" to report that the target appeared on the right side of the display. The latency between the onset of the stimulus array and the keypress was recorded for each trial. When the response was correct, the stimulus array disappeared leaving only the fixation cross on the screen for 750 ms, followed by the presentation of the stimulus array for the next trial. When participants made an error, a white screen with the word "Incorrect" in the middle appeared for 750 ms, followed by the screen containing just the fixation mark for 750 ms until the stimulus array for the next trial appeared.

Each participant completed six replications of every combination of target size (two levels), target quadrant (four levels), target digit (two levels: "2" and "3" for the small-target condition, "8" and "9" for the large-target condition), and distractor ratio (three levels), for a total of 288 experimental trials. After completing half of the trials, participants were invited to take a short break and reminded that for the remainder of the experiment the target's physical and numerical size would switch. Except for the blocking of the target's size, all other variables were randomly intermixed. The first six trials overall and the first six trials after the break were practice so participants carried out a total of 300 (288 experimental + 12 practice) trials, lasting approximately 15 min. Results from error and practice trials were excluded from analysis.

Results

For each participant in each of six conditions (3 Distractor Ratios × 2 Target Sizes), a trimming program removed all RTs that were either greater than the mean plus three standard deviations for that participant and condition, or less than 100 ms; a total of 1.9% of data points were removed. Error rates (the number of trials for which participants gave the wrong response divided by the total number of trials in that condition, and shown in Table 1) were submitted to a 3 × 2 × 2 ANOVA with distractor ratio and target size as within-subjects factors, and block order (small target

Table 1
Mean Error Rates (Percent)

Experiment and conditiion	Distractor ratio		
	2/10	6/6	10/2
Experiment 1			
Small target	1.93	1.49	1.64
Large target	.89	.74	.60
Experiment 2			
Small target	1.19	1.49	2.53
Large target	2.23	2.53	1.49
Experiment 3			
No color cue	1.30	1.67	2.23
Color cue	1.34	1.34	1.79

first or large target first) as a between-subjects factor. The effect of target size was significant, $F(1, 12) = 7.52$, $p = .018$, $\eta_p^2 = .39$. Error rates were lower in the large-target condition than the small-target condition, but RTs were also faster in the large-target condition, so there was no evidence of a speed–accuracy trade-off between conditions. None of the other main effects or interactions from the analysis of error rates were significant (all *p*s > .2), and error rates were not analyzed further.

Mean correct RTs were submitted to a 3 × 2 × 2 ANOVA with distractor ratio and target size as within-subjects factors and block order as a between-subjects factor. The main effect of block order and all interactions with block order as a factor were not significant (all *p*s > .2), so the data depicted in Figure 3 represent RTs pooled across both levels of block order. The main effect of distractor ratio was significant, $F(2, 24) = 397.5$, $p < .001$, $\eta_p^2 = .97$, indicating that RTs increased with the number of items that shared the target's physical size. Contrasts confirmed that the linear trends were significant for small targets, $F(1, 24) = 713.2$, $p < .001$, $\eta_p^2 = .97$, and for large targets, $F(1, 24) = 159.6$, $p < .001$, $\eta_p^2 = .87$, but the quadratic trends were not significant for either condition (both *F*s < 1). Responses were significantly faster for large targets than small targets, $F(1, 12) = 69.9$, $p < .001$, $\eta_p^2 = .85$.

The significant interaction between target size and distractor ratio, $F(2, 24) = 24.1$, $p < .001$, $\eta_p^2 = .67$, appears to be driven primarily by a steeper RT function for small targets than for large targets. Because RTs in both target size conditions increased with the number of items that had the target's physical size, we used the set sizes of items with the target's physical size to calculate slopes. The mean search slopes were 65 ms/item for small targets and 32 ms/item for large targets, indicating that search was much less efficient than in previous size congruity visual searches (6 ms/item when searching by physical size, 11 ms/item when searching by numerical size; Sobel et al., 2016). The disparity in slopes between the previous and present results may be partially attributable to the fact that in Sobel et al., participants could attend to just one of the target's size dimensions, but here participants needed to attend to both of the target's size dimensions. Also, because salience is a function of the difference between one item's features and the features of adjacent items (Michael & Gálvez-García, 2011), search items that are members of the smaller feature-defined subset are more salient than members of the larger subset, which could have reduced RTs for displays with two distractors that had the target's physical size and increased RTs for displays with 10 distractors that had the target's physical size.

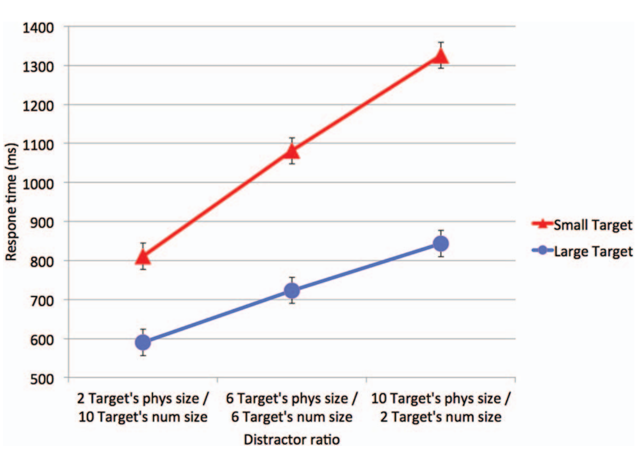

Figure 3. Response times as a function of distractor ratio in Experiment 1. Error bars represent 95% confidence intervals (Loftus & Masson, 1994). See the online article for the color version of this figure.

Discussion

The faster and more efficient (shallower slopes) search for large targets than for small targets is consistent with previous work in which larger (Proulx, 2010; Proulx & Egeth, 2008) and brighter (Braun, 1994; Nothdurft, 2006) items capture attention more than smaller and dimmer items. Of the three hypothesized patterns of RT as a function of distractor ratio, the significant effect of distractor ratio and significant linear trends support the third hypothesis, in which participants could restrict their search to the subset of items that shared the target's physical size but not the subset of items that shared the target's numerical size. This suggests that physical and numerical size of digits are processed separately, and that numerical size is unlikely to be a guiding feature in visual search.

Another way to explain participants' reliance on physical size to guide their search is the possibility that physical size captures attention regardless of the other feature that defines the target. Indeed, Proulx (2007) found that a physical size singleton captured attention in a search for a conjunction of color and orientation, but color did not capture attention in a search for a conjunction of physical size and orientation. To find out whether physical size would dominate search regardless of the other target feature, in Experiment 2, numerical size was color coded such that numerically small items were red and numerically large items were green. If physical size guides search regardless of the other target-defining feature, RTs should increase monotonically with distractor ratio as in Experiment 1. If, however, participants can restrict their search to the target-color group of items when it is the smaller set, RTs should describe an inverted-V function of distractor ratio as in the middle panel of Figure 2.

Experiment 2: Color as a Cue for Numerical Size

Method

Participants. A total of 14 UCA undergraduate students (11 female, three male) between the ages of 18 and 23 years ($M = 20.0$) volunteered for Experiment 2 in exchange for course credit. None had participated in the previous experiment.

Stimuli and procedure. The stimuli, instructions, and conditions were the same as in Experiment 1 except that numerically small items were red (Commission Internationale de L'Eclairage x/y coordinates of .61/.33, with a luminance of 32 cd/m^2) and numerically large items were green (.28/.57, 32 cd/m^2). With the same instructions as in Experiment 1, there was no mention that color was a cue to numerical size.

Results

The same trimming program used in Experiment 1 removed a total of 2.1% of data points. The analysis of error rates revealed no significant main effects or interactions (all $ps > .1$), and were not analyzed further. Mean correct RTs were submitted to a 3 × 2 × 2 ANOVA with distractor ratio and target size as within-subjects factors, and block order as a between-subjects factor. The significant interaction between block order and target size, $F(1, 12) = 8.49$, $p = .013$, $\eta_p^2 = .41$, was evidence of a practice effect: Search for small targets was faster for participants who searched for small targets in the second block than for participants who searched for small targets in the first block, and likewise for large targets. However, the main effect of block order and all other interactions with block order as a factor were not significant (all $ps > .05$), so the data depicted in Figure 4 represent RTs pooled across both levels of block order.

The main effect of distractor ratio was significant, $F(2, 24) = 9.66$, $p = .001$, $\eta_p^2 = .44$, but as can be seen in Figure 4, RTs did not increase monotonically with distractor ratio as in Experiment 1. Contrasts confirmed that the quadratic trend was significant for small targets, $F(1, 24) = 18.7$, $p < .001$, $\eta_p^2 = .43$, and marginally significant for large targets, $F(1, 24) = 3.54$, $p = .063$, $\eta_p^2 = .13$. Apparently, for large targets, the difference between the fastest and slowest responses was not sufficient to reveal a significant quadratic trend. For both the small- and large-target conditions, neither linear trend was anywhere near significant (both $Fs < 1$). Responses were significantly faster for large targets than small targets, $F(1, 12) = 18.0$, $p = .001$, $\eta_p^2 = .60$. Unlike in Experiment 1, the interaction between target size and distractor ratio was not significant, $p = .148$.

Discussion

Based on the results in Proulx (2007), we hypothesized that participants in Experiment 1 restricted their search to the items with the target's physical size because physical size would capture attention regardless of the other target-defining feature. The quadratic trends in Experiment 2 undermine this hypothesis, insofar as participants were able to restrict their search to the target-color group when it was the smaller group. This supports the original conclusion we drew from Experiment 1 that numerical size is not a guiding feature for visual search, but the question arises why our Experiment 2 results conflicted with those in Proulx.

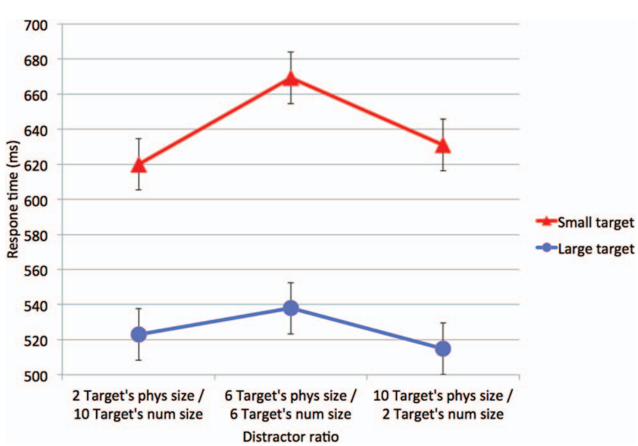

Figure 4. Response times as a function of distractor ratio in Experiment 2. Error bars represent 95% confidence intervals (Loftus & Masson, 1994). To show detail, the *y*-axis has a narrower range than in Figures 3 and 5. See the online article for the color version of this figure.

One relevant methodological difference concerns the role of color. In Proulx (2007), the color singleton was the target in some trials and one of the distractors in other trials, so participants had an incentive to adopt a top-down strategy to ignore color, which would conflict with the bottom-up salience of the color singleton. In contrast, in our Experiment 2 color was a reliable cue to one of the target's features (red for numerically small targets, green for numerically large targets), so participants had an incentive to adopt a top-down strategy to attend to color. Thus, when the target-color group was the smaller group, bottom-up salience and top-down strategy worked together.

The fact that color wrested control from physical size in our Experiment 2 when both bottom-up and top-down activation of color worked together, but not in Proulx (2007) when bottom-up and top-down conflicted, suggests that if we boost the bottom-up salience of numerical size and encourage the adoption of a top-down strategy for numerical size, participants may restrict their search to the group of items with the target's numerical size when it is the smaller group. In turn, such an effect would provide evidence that numerical size can be a guiding feature. A reasonable way to boost the salience of numerical size would be to increase the numerical distance between the smallest and largest numbers. However, using 2s and 3s as numerically small items, and 8s and 9s as numerically large items, as we did, stretches numerical distance as far as possible for single-digit numerals (without including the Digit 1, which has a very different shape than other digits). We limited the stimulus set to single-digit numerals because using numerals containing more than single digits serves to boost the salience of the *physical* size differences (Sobel et al., 2016).

In Experiment 3, we left numerical distance the same as in previous experiments, and relied on two methods to reduce the bottom-up salience of physical size. First, because search was faster and more efficient for physically large targets than small targets in Experiments 1 and 2, all displays in Experiment 3 contained physically small targets. Second, reducing the difference between one feature's highest and lowest values encourages participants to restrict their search to the group that shares the other feature with the target (Kaptein, Theeuwes, & van der Heijden, 1995; Sobel & Cave, 2002), so in Experiment 3, the physical size difference between the physically large and small items was reduced relative to the previous experiments. To induce a top-down advantage for numerical size over physical size in Experiment 3, we relied on the fact that when one of the feature-defined distractors is less numerous in a majority of trials, participants tend to adopt a top-down strategy to restrict their search to the feature-defined group that is generally less numerous (Bacon & Egeth, 1997; Sobel, Gerrie, Poole, & Kane, 2007).

As a test to determine whether reducing bottom-up salience of physical size and boosting the top-down advantage of numerical size would discourage search through the group with the target's physical size, in one condition, we pitted physical size against a feature we already knew was a guiding feature: color. In the color-cue condition, numerically small items were red and numerically large items were green, as in Experiment 2. If the bottom-up and top-down disadvantages of physical size in the color-cue condition encourage participants to restrict their search to the target-color group, there should be a linear trend in the opposite direction to that observed in Experiment 1. To see whether this linear trend would persist in the absence of a color cue for numerical size, in a second condition all search items were the same color. If participants can restrict their search on the basis of numerical size, RTs should be faster for displays containing two items with the target's numerical size than displays containing six items with the target's numerical size. Such a pattern of data would provide evidence that numerical size is a guiding feature in visual search.

Experiment 3: Bottom-Up and Top-Down Disadvantages for Physical Size

Method

Participants. A total of 30 UCA undergraduate students (23 female, seven male) between the ages of 18 and 36 years (M = 21.9) volunteered for Experiment 3 in exchange for course credit. None had participated in either of the previous experiments. The results from two participants were excluded from analysis because of noncompliance with instructions.

Stimuli and procedure. Participants were randomly assigned to one of two conditions; in the color-cue condition, numerically small digits were red and numerically large digits were green, whereas in the no-color-cue condition, all digits were white. For all participants, the target was physically and numerically small on every trial, and as in previous experiments, the instructions did not mention anything about the digits' colors. To reduce the size contrast between the smallest and largest physical sizes relative to the previous experiments, the mean physical size was the same, but the difference between each digit's physical size and the mean physical size was cut in half. As a result, the Target Digit 2 and Distractor Digit 9 were 0.64° wide × 1.28° tall, the Target Digit 3 and Distractor Digit 8 were 0.72° wide × 1.44° tall, the Distractor Digit 3 was 1.15° wide × 2.30° tall, and the Distractor Digit 2 was 1.23° wide × 2.46° tall. Because all targets were physically and numerically small, 8s and 9s were never targets.

To encourage participants to adopt a strategy to restrict their search to the group of items with the target's numerical size, in a majority of experimental trials (192 of 288), displays contained two distractors that shared the target's numerical size and 10 that shared the target's physical size. In one third as many trials (n = 64), displays contained six distractors that shared the target's numerical size, and in one sixth as many trials (n = 32), displays contained 10 distractors that shared the target's numerical size. The first six trials overall and the first six trials after a break halfway through the experiment were practice, for a total of 300 (192 + 64 + 32 = 288 experimental + 12 practice) trials.

Results

For each participant in each of three distractor ratio conditions, a trimming program removed all RTs that were either greater than the mean plus three standard deviations for that participant and condition or less than 100 ms; a total of 1.8% of data points were removed. Error rates were submitted to a 3 × 2 ANOVA with distractor ratio as a within-subjects factor and color cue as a between-subjects factor. The main effects and their interaction were not significant (all ps > .1), and error rates were not analyzed further.

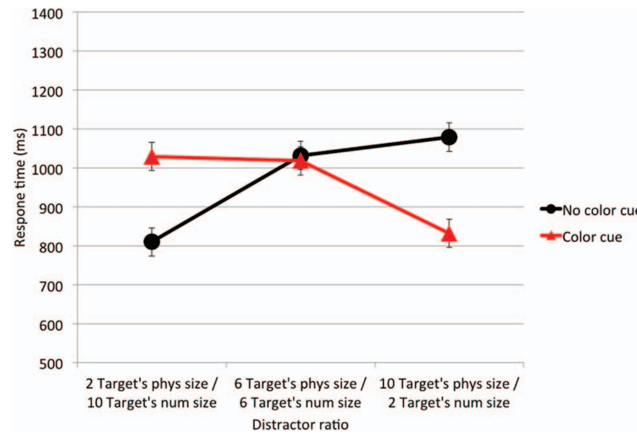

Figure 5. Response times as a function of distractor ratio in Experiment 3. Error bars represent 95% confidence intervals (Loftus & Masson, 1994). See the online article for the color version of this figure.

Mean correct RTs (depicted in Figure 5) were submitted to a 3 × 2 ANOVA with distractor ratio as a within-subjects factor and color cue as a between-subjects factor. The main effect of distractor ratio was significant, $F(2, 52) = 13.7$, $p < .001$, $\eta_p^2 = .35$, which appears to be driven by the longer mean RTs for the 6/6 distractor ratio than the other two distractor ratios. The main effect of color cue was not significant, $p = .88$, but the interaction between distractor ratio and color cue was significant, $F(2, 52) = 64.9$, $p < .001$, $\eta_p^2 = .71$, indicating that RTs increased in the opposite direction in the color-cue condition than the no-color-cue condition. Contrasts confirmed that the linear trends were significant for the color-cue condition, $F(1, 52) = 46.4$, $p < .001$, $\eta_p^2 = .47$, and the no-color-cue condition, $F(1, 52) = 86.3$, $p < .001$, $\eta_p^2 = .62$, and that the linear trends increased in opposite directions between conditions, $F(1, 52) = 129.7$, $p < .001$, $\eta_p^2 = .71$.

Mean slopes were −25 ms/item for the color-cue condition and 34 ms/item for the no-color-cue condition, numbers that are more akin to the large-target condition in Experiment 1 (32 ms/item) than the small-target condition (65 ms/item). The shallower slopes in Experiment 3 than the small-target condition in Experiment 1 appears to be attributable to a kink in each of the color-cue conditions' data plots, suggesting that each function contains a blend of linear and quadratic trends. Contrasts confirmed that the quadratic trend was significant for the color-cue condition, $F(1, 52) = 12.2$, $p < .001$, $\eta_p^2 = .18$, and the no-color-cue condition, $F(1, 52) = 12.2$, $p < .001$, $\eta_p^2 = .18$. The larger effect sizes for the linear trends ($\eta_p^2 = .47$ and .62) than the quadratic trends ($\eta_p^2 = .18$) show that the linear trends predominate.

To compare the linear and quadratic trends from Experiment 3 with those from the previous experiments, we carried out additional analyses with experiment as a factor. The results from the color-cue condition in Experiment 3 and the small-target condition in Experiment 2 were submitted to a 3 × 2 ANOVA with distractor ratio as a within-subjects factor and experiment as a between-subjects factor. The main effects of distractor ratio, $F(2, 52) = 21.1$, $p < .001$, $\eta_p^2 = .45$, and experiment, $F(1, 26) = 20.7$, $p < .001$, $\eta_p^2 = .44$, and their interaction, $F(2, 52) = 16.8$, $p < .001$, $\eta_p^2 = .39$, were all significant. Contrasts showed that the linear trend was significantly stronger in the color-cue condition of

Experiment 3 than the small-target condition of Experiment 2, $F(1, 52) = 31.7$, $p < .001$, $\eta_p^2 = .38$, but the quadratic trends were not significantly different between Experiments 2 and 3, $p = .18$. Next, the results from the no-color-cue condition in Experiment 3 and the small-target condition in Experiment 1 were submitted to a 3×2 ANOVA with distractor ratio as a within-subjects factor and experiment as a between-subjects factor. The main effect of distractor ratio, $F(2, 52) = 278.7$, $p < .001$, $\eta_p^2 = .91$, and the interaction between distractor ratio and experiment, $F(2, 52) = 30.3$, $p < .001$, $\eta_p^2 = .54$, were significant, but the main effect of experiment was not, $p = .23$. Contrasts showed that the linear trend was significantly stronger in the small-target condition of Experiment 1 than the no-color-cue condition of Experiment 3, $F(1, 52) = 53.9$, $p < .001$, $\eta_p^2 = .51$, and the quadratic trend was significantly stronger in the Experiment 3 no-color-cue condition than the Experiment 1 small-target condition, $F(1, 52) = 6.58$, $p = .012$, $\eta_p^2 = .11$.

Discussion

The linear trend in the color-cue condition shows that inducing a bottom-up and top-down disadvantage for physical size interfered with its ability to guide search. However, the opposite linear trend in the no-color-cue condition shows that this effect did not persist when the color cue was removed. In both conditions, the most prevalent distractor ratio (i.e., 10 distractors shared the target's physical size and two distractors shared the target's numerical size) was 6 times more common than the least prevalent distractor ratio (i.e., two distractors shared the target's physical size and 10 distractors shared the target's numerical size). Participants in the color-cue condition were able to exploit this skewed prevalence, and RTs were fastest for the most prevalent distractor ratio, but in the no-color-cue condition, RTs were *slowest* for the most prevalent distractor ratio. Without a color cue, participants restricted their search to the items with the target's physical size, even though this was the larger group in the majority of displays.

The results from both conditions contained a blend of a linear trend and a quadratic trend, although the effect size for the linear trends was much greater than for the quadratic trends, indicating that the bias for one of the target's features (i.e., color in the color-cue condition, physical size in the no-color-cue condition) was the predominant factor guiding search. Nevertheless, the presence of quadratic trends requires some explanation. The color-cue condition included color and physical size, both of which are guiding features (Wolfe & Horowitz, 2004). Reducing the bottom-up salience of physical size and encouraging a top-down strategy to search through the target-color group in Experiment 3 induced a bias for the target-color group, but some activation for physical size remained. In the no-color-cue condition, search was primarily restricted to the items with the target's physical size, but the modest quadratic trend indicates that numerical size influenced search. Although this evidence is consistent with several recent studies showing that numerical size can *influence* search (Godwin et al., 2014; Krause et al., 2016; Schwarz & Eiselt, 2012; Sobel et al., 2015, 2016), does that mean that numerical size *guides* search? As mentioned previously, in distractor ratio search, a guiding feature elicits bottom-up activation when the items with that feature constitute the smaller of two groups (Poisson & Wilkinson, 1992; Sobel & Cave, 2002), as indicated by faster RTs than when both feature-defined groups are the same size. The quadratic trend indicates that the RT function has a point of deflection, but this was not enough to show that numerical size is a guiding feature: RTs were not faster when the group of items with the target's numerical size was the smaller group than when the two groups were the same size. Although the results from Experiment 3 failed to provide evidence that numerical size is a guiding feature, the possibility remains that future experiments could reveal numerical size to be a guiding feature.

General Discussion

The size congruity effect, in which the selection of one of two numbers on the basis of physical or numerical size is faster when both sizes are congruent than when incongruent, is a robust and frequently replicated experimental result. The effect demonstrates that physical and numerical size interact mentally, but the traditional two-item task is insufficiently sensitive to determine whether the interaction occurs at an early representational stage or at a later decision stage. In three experiments, we sought to move beyond the traditional size congruity paradigm, and employed a distractor ratio conjunction search task to pit physical size and numerical size against each other in a tug-of-war.

Experiment 1 showed that physical and numerical size are processed separately, and suggested that physical size but not numerical size can guide visual search. Because a physical-size singleton captures attention in a conjunction search, but a color singleton does not (Proulx, 2007), Experiment 2 addressed the possibility that physical size would guide search regardless of the other target-defining feature. In Experiment 2, participants restricted their search to the smaller of two feature-defined (either physical size or color) subsets, undermining this hypothesis. Experiment 3 was designed to test a second alternative explanation for the evidence from Experiment 1 that physical size but not numerical size can guide search: perhaps physical size needs to suffer bottom-up and top-down disadvantages for any evidence of numerical size as a guiding feature to emerge. The results from the color condition indicated that our stimuli were sufficient to interfere with the ability of physical size to guide search. This effect was reversed when the color cue was removed, indicating that physical size guided search even though items with the target's physical size predominated in most displays. Experiment 3 did reveal some evidence that numerical size can *influence* search, but this does not, in turn, imply that numerical size can *guide* search, because search was not restricted to the group of items with the target's numerical size when that group was smaller than the group of items with the target's physical size.

The dubious status of numerical size as a guiding feature corroborates the doubt expressed by Wolfe and Horowitz (2004), which reflected some of the difficulties experienced by prior researchers looking at the role of semantic associations in visual search. Jonides and Gleitman (1972) found that search performance depended on whether an "O" target was categorized by participants as a letter or the number zero, but Duncan (1983) failed to replicate this effect. Because manipulating semantic associations typically entails a confounding manipulation of shape (e.g., 9 is numerically larger than 2, but also has a different shape), Krueger (1984) argued that any effect of semantic association on visual search can be more parsimoniously explained in terms of visual features. Nevertheless, researchers have recently developed various techniques to tease out the role of semantic associations in visual search by carefully controlling visual features (Godwin et al., 2014; Lupyan, 2008; Lupyan & Spivey, 2008; Schwarz & Eiselt, 2012; Sobel et al., 2015, 2016).

Taken together, these studies have firmly established the fact that semantic associations can affect visual search, but this does not necessarily imply that numerical size is a guiding feature that affects perceptual processing per se. For example, search is faster when target digits are adjacent on the number line than when they are numerically distant (Sobel et al., 2015). However, the authors argued that a target template containing adjacent digits is simpler and therefore easier to maintain in working memory than when the target digits are numerically distant. Working memory is implicated in the cognitive but not perceptual contributions to visual search (Kane, Poole, Tuholski, & Engle, 2006; Sobel et al., 2007). This argument that numerical quantities affect search primarily through working memory can be extended to other studies showing that target-distractor numerical distance affects search efficiency (Schwarz & Eiselt, 2012) and eye fixations (Godwin et al., 2014), as well as the present study, in which numerical size influenced visual search but provided no evidence that search could be restricted to the group of items with the target's numerical size.

Distinguishing between the cognitive processing of numerical size and perceptual processing of physical size enables us to reconcile the present results, in which numerical size is not a guiding feature in visual search, with the previous work showing that numerical magnitude of targets and distractors affects visual search performance. It can also help explain why processing of the physical and numerical sizes of digits seems prima facie to be driven by fundamentally distinct mechanisms. First of all, a digit's physical size can be directly extracted from its visual appearance, whereas determining a digit's numerical size entails the extra step of connecting the digit's visual appearance with symbols stored in memory (Lupyan, Thompson-Schill, & Swingley, 2010; Schwarz & Heinze, 1998). Second, although the ability to appreciate an object's physical size is beneficial to all human and nonhuman individuals, connecting a digit's shape to its associated numerical size is a skill based on long hours of deliberate practice. These disparities between the processing of physical and numerical quantities are validated by our results, and the results from a growing set of studies that are inconsistent with an early interaction model in which spatial and numerical magnitude are encoded in the same mental representation (Antoine & Gevers, 2016; Arend & Henik, 2015; Cohen Kadosh, Gevers, & Notebaert, 2011; Faulkenberry et al., 2016; Santens & Verguts, 2011; Sobel et al., 2016).

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