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Target grouping in visual search for multiple digits

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Abstract In four experiments in which participants searched for multiple target digits we hypothesized that search should be fastest when the targets are arranged closely together on the number line without any intervening distractor digits, i.e., the targets form a contiguous and coherent group. In Experiment 1 search performance was better for targets defined by numerical magnitude than parity (i.e., evenness); this result supports our hypothesis but could also be due to the linear separability of targets from distractors or the numerical distance between them. Experiment 2 controlled for target-distractor linear separability and numerical distance, yielding faster search when targets were surrounded by distractors on the number line than when they surrounded distractors. This result is consistent with target contiguity and coherence but also with grouping by similarity of target shapes. Experiment 3 controlled for all three alternative explanations (linear separability, numerical distance, and shape similarity) and search performance was better for contiguous targets than separated targets. In Experiment 4 search performance was better for a coherent target group than one with intervening distractors. Of the possibilities we considered, only the hypothesis based on the contiguity and coherence of the target group on the number line can account for the results from all four experiments.

Keywords Visual search · Working memory · Text comprehension

Introduction

According to the classical perception-cognition divide, visual processing proceeds without interference from higher-level cognition, or in other words perception can be considered to be cognitively impenetrable (Pylyshyn, 1999). The notion that visual perception is cognitively impenetrable enjoys widespread support from the vast and ever-increasing collection of visual illusions for which the illusory appearance persists in spite of knowledge that is inconsistent with the visual experience (Firestone & Scholl, 2014). For example, even if the observer knows that the two lines in the Müller-Lyer illusion (1889) are equally long, the Y-terminated line appears to be longer than the arrow-terminated line. Nevertheless, a growing body of evidence has found that language can influence visual perception. Presenting a verbal label can enhance the ability to detect an object that is rendered invisible by continuous flash suppression (Lupyan & Ward, 2013), to identify the motion direction of dots at motion coherence threshold (Meteyard, Bahrami, & Vigliocco, 2007), and to distinguish between intact and distorted versions of high-level stimuli such as faces (Puri & Wojciulik, 2008). Here we investigate the interaction between perception and cognition in visual search for digits that are semantically associated with the numerical quantities they represent.

Historically, attempts to uncover a role for the semantic associations of letters and numbers in visual search experiments have been hindered by the fact that manipulating the semantic associations of alphanumeric characters typically entails also manipulating the characters' perceptual features (i.e., among single-digit numbers 2 is numerically small and 9 is numerically large but the two characters also have different shapes). As a result, it is difficult to disentangle conceptual and perceptual effects on search (Krueger, 1984), to such an extent that Wolfe and Horowitz (2004) expressed doubt that alphanumeric concepts could guide search. As Wolfe (1998) notes, while many visual search tasks have used alphanumeric characters as targets and distractors, such tasks might in fact be perceptual feature searches in the guise of alphanumeric searches.

Nevertheless, by carefully controlling the shape of the items used in visual search, Lupyan (2008) showed that the *semantic* heterogeneity of distractors can influence search

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efficiency. The target shape in his experiments looked like the thorn character in Old English (þ) that appears to modern eyes as a blend of 'p' and 'b'. In one condition participants searched for the þ target among the distractors B and b (same letter), and in another they searched among the distractors B and p (different letters). Search was more efficient when distractors were (semantically) the same than when they were different, indicating that the well established principle that search efficiency increases with the perceptual similarity of distractors (Duncan & Humphreys, 1989) extends to semantic similarity.

In light of the fact that the meanings associated with letters can influence search, it is reasonable to wonder how the quantities associated with numerical characters affect visual search. Numbers are commonly presumed to be arranged along a mental number line (Feigenson, Dehaene, & Spelke, 2004; Pinhas, Pothos, & Tzelgov, 2013), analogous to a one-dimensional perceptual feature space. In a recent study (Schwarz & Eiselt, 2012) participants searched for a target digit 5 among distractor digits at various numerical distances from the target. Search speed increased with the target-distractor numerical distance, and replacing the 5 with a visually similar S abolished the effect, implying that it was driven by the numerical quantity associated with the digit rather than its shape.

Godwin, Hout, and Menneer (2014) developed two key extensions to the Schwarz and Eiselt (2012) study. First, they broadened the target set from the single digit used by Schwarz and Eiselt to include all the digits from 0 to 9 in order to eliminate the possibility that the effect of numerical distance was attributable to some visual quirk peculiar to the digit 5. Second, instead of controlling the visual characteristics of the target and distractors, Godwin et al. used multidimensional scaling to create a space representing the visual similarity between digits. Thus armed with metrics of visual similarity (the two-dimensional similarity map) as well as numerical similarity (the number line), Godwin et al. found that both factors affected eye fixations. Apparently, the visual processing required to distinguish target digits from distractors is a function of their relative locations in a representational space encompassing perceptual properties as well as higher-level properties (in this case, numerical size). As Lupyan (2008) did for distractor-distractor similarity, these findings extend the results of Duncan and Humphreys (1989) regarding target-distractor perceptual differences into the realm of semantic differences.

Here we build on previous work showing that search efficiency increases with distractor-distractor semantic similarity (Lupyan, 2008) and target-distractor semantic differences (Godwin et al., 2014; Schwarz & Eiselt, 2012) by looking at target-target semantic similarity in visual search for multiple targets. In recent visual search experiments for multiple targets, search efficiency was shown to increase with target-target perceptual similarity (Menneer, Cave, & Donnelly, 2009; Stroud, Menneer, Cave, & Donnelly, 2012). With these results in mind, we hypothesized that visual search for multiple target digits should be most efficient when the target digits' numerical representations form a contiguous and coherent (i.e., no intervening distractors) group on the number line than when they don't. At the same time we recognized the need to control for alternative explanations; in terms of perceptual properties, search efficiency might depend on the similarity between target shapes or the brightness of targets. As for semantic properties, search efficiency might depend on the numerical distance between targets and distractors. Finally, keeping in mind the fact that visual search for a color-defined target is more efficient when the target color is linearly separable from distractor colors in color space than when it is not (Bauer, Jolicoeur, & Cowan, 1996a, 1996b, 1998; D'Zmura, 1991), another alternative explanation that points to semantic influences is that search efficiency might depend on the linear separability of targets from distractors on the number line.

As a preliminary test of our hypothesis that search efficiency increases with target contiguity and coherence, in Experiment 1 targets were distinguished from distractors by their numerical magnitude in one condition and by their parity (i.e., evenness) in another condition. For a given set of digits, the subset that contains numerically smaller digits can form a contiguous and coherent group on the number line, whereas even digits are spread across a wider expanse of the number line and are interleaved with odd digits. Thus targets were contiguous and coherent in the magnitude condition but not in the parity condition.

Experiment 1: Targets defined by numerical magnitude or parity

Method

Participants In light of recent studies that have revealed an effect of numerical magnitude on visual search (Godwin et al., 2014; Reijnen, Wolfe, & Krummenacher, 2013; Schwarz & Eiselt, 2012), we anticipated a similarly large effect of d = 1.25, for which a minimum of 14 participants per group would be needed to achieve 80 % power at an α of 0.05 (Bausell & Li, 2002). We obtained permission to carry out the experiment from the University of Central Arkansas Institutional Review Board before gathering any data, and treated participants in accordance with the ethical guidelines stipulated by the Amercian Psychological Association (APA). A total of 28 undergraduate students (two groups of 14) from the University of Central Arkansas volunteered for the experiment in exchange for class credit.

Apparatus The experiment was conducted on a Mac G4 computer with a screen resolution of 1024 × 768 pixels. A program written in Real Studio Basic presented stimulus arrays to participants and gathered responses from the keyboard.

Stimuli In order to reduce shape differences between digits, we constructed versions of the digits 2 through 9 from line segments as on the faces of digital clocks and depicted in the upper portion of Fig. 1. Further, in order to reduce shape differences between conditions, we used the same set of six digits in both conditions: 2, 3, 4, 7, 8, and 9. At a viewing distance of 56 cm, each component line segment spanned 0.72° of visual angle (with the exception of the oblique edge of the '4', which spanned 1.0°), so that each digit was 0.72° wide × 1.4° tall. Digits were arranged on an imaginary circle with a radius of 5.9° and centered on a fixation cross consisting of two orthogonal line segments each 1.0° long. The fixation mark and digits were white against a black background. Three displays from the magnitude condition in which small digits were the targets are depicted in the lower portion of Fig. 1.

Participants were randomly assigned to one of two grouping conditions: magnitude and parity. In the magnitude condition, half of the participants searched for numerically small target digits (2, 3, and 4) among numerically large distractors (7, 8, and 9) and vice versa for the other half of participants. In the parity condition half of the participants searched for even targets (2, 4, and 8) among odd distractors (3, 7, and 9) and vice versa for the other half. The upper portion of Fig. 2 depicts the number line positions of targets and distractors in Experiment 1 as a way to graphically convey the contiguity and coherence of targets on the number line.

For each trial, the stimulus array contained one of the three target digits and three, six, or nine distractors (i.e., one, two, or three sets of the distractor digits) distributed evenly along the circumference of the imaginary circle. A target digit was always present, and positioned 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 target position was readily distinguishable from the vertical meridian, targets were always placed at least 30° of arc away from vertical, i.e., in terms of a clock face, targets in the upper right quadrant were placed at 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.

Procedure At the beginning of each trial the stimulus array appeared and remained visible until participants responded by pressing either the 'z' key to indicate that the target appeared on the left side of the display or the '/' key to indicate that the target appeared on the right side of the display. The time between the onset of the stimulus array and the keypress was recorded for each trial. If the correct response was made, the stimulus array disappeared leaving only the fixation cross on the screen for 750 ms, followed by 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 blank screen containing the fixation mark for 750 ms until the stimulus array for the next trial appeared. Each participant completed ten replications of every combination of quadrant (four levels), target (three levels), and

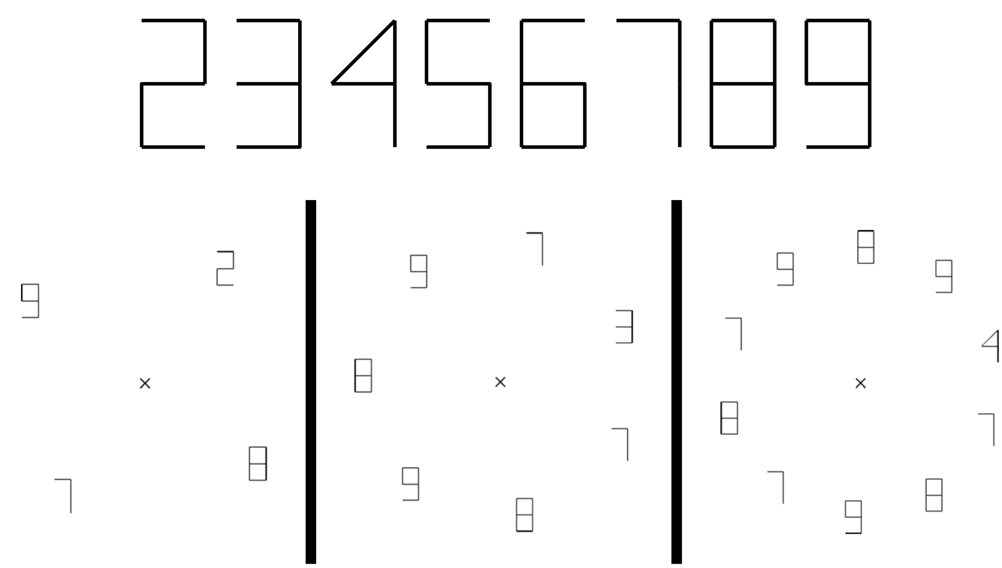

Fig. 1 The upper panel shows the digits we built from line segments and used in all experiments. The lower panel shows stimulus displays containing four, seven, and ten items respectively in the magnitude condition with small targets in Experiment 1. In all three displays the target digit (2, 3, or 4) is on the right side of the display

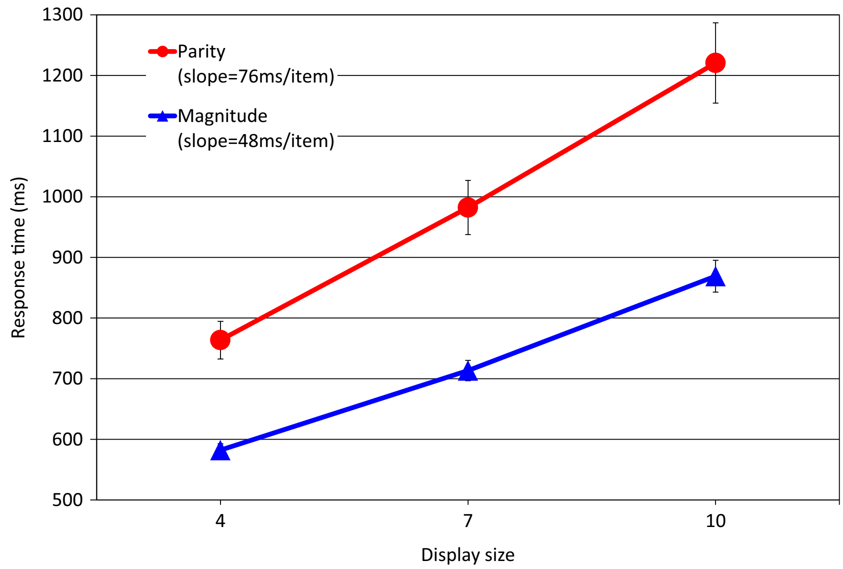

Fig. 2 Number line positions of target and distractor digits in Experiment 1 (target digits are enclosed by a box) and response times (RTs) as a function of display size. Although the digits on the number line appear in a commonly used typeface, the digits used in our experiments were presented in the digital clock font shown in Fig. 1. Error bars indicate standard errors of the means

display size (three levels), for a total of 360 experimental trials. After completing half of the trials participants were allowed to take a short break. The first six trials overall and the first six trials after the break were considered practice so participants carried out a total of 372 (360 experimental + 12 practice) trials, lasting approximately 20 minutes. Results from error and practice trials were excluded from response-time (RT) analysis.

Results and discussion

Independent samples t-tests showed no differences in RTs between small and large targets in the magnitude condition or between even and odd targets in the parity condition (both *ps* > .1); in subsequent analyses we pooled the data across these sub-conditions. Mean correct RTs (depicted in Fig. 2) were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. The ANOVA revealed significant main effects of grouping condition, $F(1, 26) = 29.8$, $p < .001$, $\eta^2 = .534$, and display size, $F(2, 52) = 225$, $p < .001$, $\eta^2 = .856$, as well as their interaction, $F(2, 52) = 11.8$, $p < .001$, $\eta^2 = .0448$. In visual search experiments the slope of RT as a function of display size is typically interpreted as the efficiency of search because a more difficult search task entails a higher processing cost per display item than an easier task, resulting in steeper slopes. A t-test comparing the slopes of the RT functions across grouping conditions was significant, $t(26) = 3.71$, $p = .001$, $\eta^2 = .346$. Mean error rates were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. No effects were significant, and error rates were not further analyzed.

The faster (shorter overall RT) and more efficient (shallower slopes) search in the magnitude condition than the parity condition is consistent with our hypothesis that search is easier when the target digits form a contiguous and coherent (no intervening distractors) group on the number line. However, there are at least two other possible ways to explain the observed differences between the magnitude and parity conditions. First, small digits (2, 3, and 4) can be segregated from large digits (7, 8, and 9) in the magnitude condition by drawing a single straight boundary line between the two groups, but to segregate even digits (2, 4, and 8) from odd (3, 7, and 9) as in the parity condition requires several boundary lines. Just as a search for a color-defined target is more efficient when the target color is linearly separable from distractor colors than when it is not (Bauer et al., 1996a, 1996b, 1998; D'Zmura, 1991), search was more efficient when the target digits were linearly separable on the number line from distractors (magnitude condition) than when they were not (parity condition). Second, the target-distractor numerical distance was larger in the magnitude condition (mean numerical distance between every pair of targets and distractors = 5) than the parity condition (mean numerical target-distractor distance = 3.2). As in Schwarz and Eiselt (2012), search was more efficient when the target-distractor numerical distance was larger (magnitude condition) than when the target-distractor numerical distance was smaller (parity condition).

Experiment 2 was designed to manipulate the contiguity and coherence of the target group on the number line while controlling both the linear separability of targets from distractors and the target-distractor numerical distance. We selected targets (5 and 6) that are surrounded on the number line by distractors (3 and 8) in one condition (inner targets), and targets (3 and 8) that surround distractors (5 and 6) in another condition (outer targets). In neither condition were the targets linearly separable from distractors, and because the targets in one condition were the distractors in the other condition, the target-distractor numerical distance was the same in both conditions. Thus, target-distractor linear separability and numerical distance were held fixed in Experiment 2, whereas the targets formed a contiguous and coherent group on the number line in the inner condition but not the outer condition.

Experiment 2: Targets surrounded by or surrounding distractors

Method

Experiment 2 was similar to Experiment 1, with the following exceptions.

Participants A total of 28 undergraduate students from the University of Central Arkansas volunteered for the experiment in exchange for class credit. None had participated in Experiment 1. Participants were randomly assigned to one of two grouping conditions.

Stimuli The same digits were used in both conditions: 3, 5, 6, and 8. In the inner condition the targets were positioned between distractors on the number line, so participants searched for targets 5 and 6 among the distractors 3 and 8; participants in the outer condition searched for targets 3 and 8 among the distractors 5 and 6. Each display contained four, six, or eight distractors and one of the two target digits.

Procedure Each participant completed 14 replications of every combination of quadrant (4 levels), target (2), and display size (3), for a total of 336 trials.

Results and discussion

Mean correct RTs (depicted in Fig. 3) were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. The main effects of grouping condition, $F(1, 26) = 11.9$, $p = .002$, $\eta^2 = .314$, display size, $F(2, 52) = 106$, $p < .001$, $\eta^2 = .777$, and the interaction, $F(2, 52) = 4.58$, $p = .015$, $\eta^2 = .0334$, were significant. A t-test comparing slopes was significant, $t(26) = 2.13$, $p = .043$, $\eta^2 = .148$. Mean error rates were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. No effects were significant, and error rates were not further analyzed.

Search was faster and more efficient when the targets were contiguous (inner targets condition) than when the distractors were contiguous (outer targets condition), suggesting that participants relied on target grouping rather than distractor grouping. However, while our results are consistent with an account based on grouping of targets by number line position, it is possible that they are also consistent with an account based on perceptual features such as luminance and shape. Because search is more efficient when the target is brighter than distractors (Proulx & Egeth, 2006), here we consider whether brightness differences could account for faster and more efficient

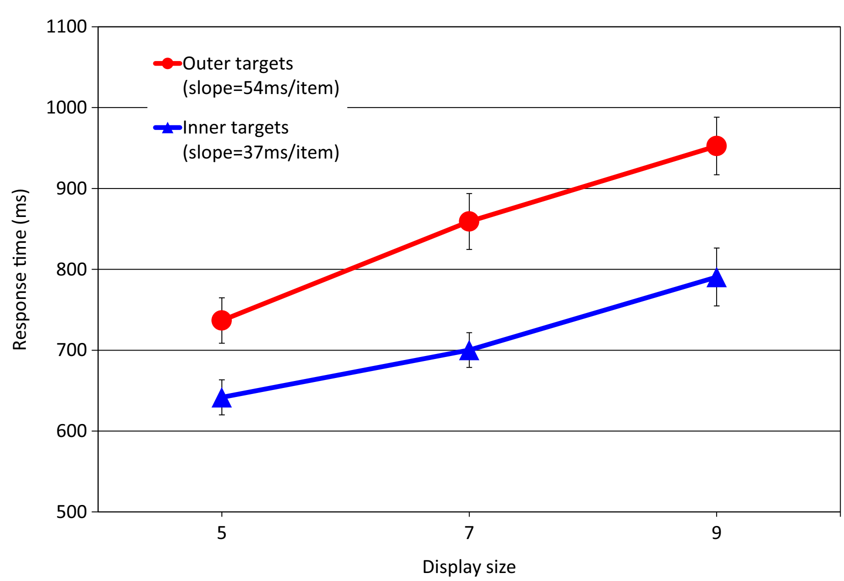

Fig. 3 Number line positions of target and distractor digits in Experiment 2 (target digits are enclosed by a box) and response times (RTs) as a function of display size. Error bars indicate standard errors of the means

search for inner targets (5 and 6) compared to outer targets (3 and 8). All digits used in this experiment consisted of line segments of equal length (and thus brightness), so the brightness of each digit is a function of how many line segments it contains. As can be seen by examining Fig. 1, the inner condition targets (5 and 6) contained five line segments and six line segments respectively for a total of 11, whereas the outer condition targets (3 and 8) contained five line segments and seven line segments respectively for a total of 12. A hypothesis based on brightness would predict faster RTs for the condition with the brighter targets (outer targets), yet this condition was *slower*, thus brightness differences fail to explain our results.

Alternatively, perhaps the shapes of the targets in the inner condition were more similar to each other – and thus more easily grouped – than in the outer condition. Cohen (2009; see also García-Orza, Perea, Mallouh, & Carreiras, 2012) recently developed a metric of physical similarity between digits like those depicted in Fig. 1, and argued that physical similarity is a better explanation than numerical distance in his and others' number comparison tasks (e.g., Moyer & Landauer, 1967; Tzelgov & Ganor-Stern, 2005). Cohen presented various digits to participants and asked them to report whether the presented digit was the same as or different than a target digit 5. When RTs from non-target trials (i.e., a digit other than 5 was presented) were regressed on two different functions, the function representing Cohen's physical similarity metric was a better fit than the function representing numerical distance. Cohen's metric states that physical similarity = O/D, where O is the number of line segments that two digits share and D is the number of non-shared line segments. Using this equation, the targets in the inner condition (5 and 6) share five line segments with one left over, yielding a physical similarity of 5/1 = 5, while the targets in the outer condition (3 and 8) share five line segments with two left over, yielding a physical similarity of 5/2 = 2.5. The shapes of the targets in the faster (inner targets) condition are indeed more similar to each other than in the slower (outer targets) condition, and consequently our Experiment 2 results are consistent with an account based on grouping by shape as well as grouping by number line position.

Accordingly, Experiment 3 was designed to manipulate the contiguity of targets on the number line while controlling similarity of target shapes by exploiting the fact that the digit 9 is a 180° rotation of the digit 6. The targets in one condition were 5 and 6 (contiguous on the number line) and in another condition were 5 and 9 (separated). According to Cohen's (2009) shape similarity metric, the shape similarity of 5 and 6 is the same as 5 and 9. Also, because Experiment 2 showed that target grouping was more essential than distractor grouping (i.e., search was faster when the targets were contiguous and coherent than when distractors were contiguous and coherent), we sought to investigate the roles of target contiguity (Experiment 3) and coherence (Experiment 4) while eliminating distractor grouping as an alternative explanation. To do so, we used the same distractor digits (3 and 4) in all conditions in Experiments 3 and 4.

Experiment 3: Targets that are contiguous or separated on the number line

Method

Experiment 3 was similar to the previous experiments, with the following exceptions.

Participants A total of 28 undergraduate students from the University of Central Arkansas volunteered for the experiment in exchange for class credit. None had participated in the previous experiments. Participants were randomly assigned to one of two grouping conditions.

Stimuli In the contiguous targets condition participants searched for the targets 5 and 6 among the distractors 3 and 4. In the separated targets condition participants searched for the targets 5 and 9 among the distractors 3 and 4. In both conditions the targets formed a coherent group because there were no intervening distractor digits.

Procedure The procedure was identical to that in Experiment 2.

Results and discussion

Mean correct RTs (depicted in Fig. 4) were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. The main effects of grouping condition, $F(1, 26) = 8.56$, $p < .001$, $\eta^2 = .248$, display size, $F(2, 52) = 136$, $p < .001$, $\eta^2 = .786$, and the interaction, $F(2, 52) = 11.1$, $p < .001$, $\eta^2 = .0641$, were significant. A t-test comparing slopes with grouping condition as a between-subjects variable was significant, $t(26) = 3.90$, $p = .001$, $\eta^2 = .369$. Mean error rates were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. No effects were significant, and error rates were not further analyzed.

Search was faster and more efficient when targets were contiguous on the number line than when separated from each other, supporting our hypothesis that contiguity of targets on the number line makes search easier. In both the contiguous targets (5 and 6) and separated targets (5 and 9) conditions the targets were linearly separable from distractors (3 and 4) on the number line, so the observed difference between grouping conditions cannot be attributed to linear separability of targets from distractors. Furthermore, targets and distractors were numerically closer in the faster and more efficient contiguous targets condition (mean numerical distance between every pair of targets and distractors = 2) than the separated targets

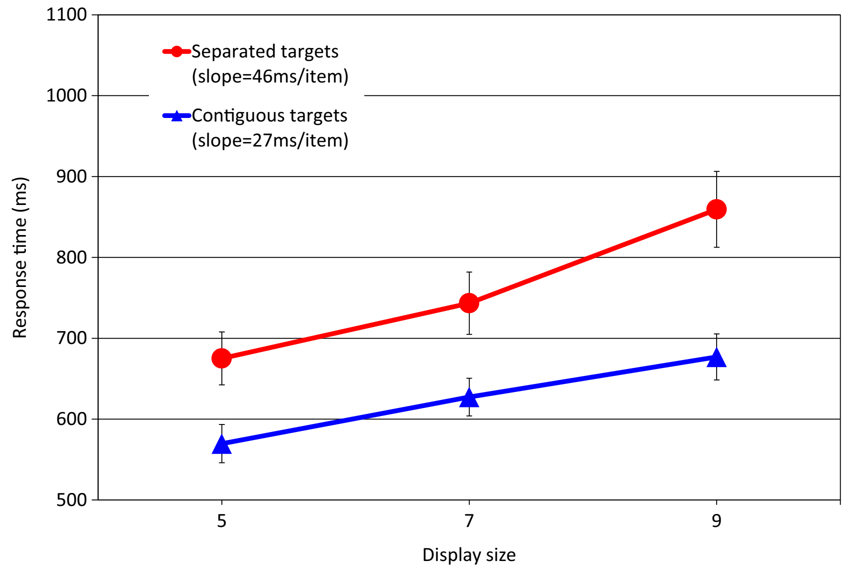

Fig. 4 Number line positions of target and distractor digits in Experiment 3 (target digits are enclosed by a box) and response times (RTs) as a function of display size. Error bars indicate standard errors of the means

condition (mean numerical target-distractor distance = 3.5). In other words, search speed and efficiency decreased as target-distractor numerical distance increased, which is opposite to the effect reported by Schwarz and Eiselt (2012), in which search speed *increased* with target-distractor numerical distance. Thus, as with Experiment 2, the results from Experiment 3 are inconsistent with hypotheses based on target-distractor linear separability and numerical distance.

What about target brightness and shape similarity? The targets in the contiguous condition (5 and 6) had the same number of line segments as the targets in the separated condition (5 and 9), so the targets were equally bright across conditions. By Cohen's (2009) metric of physical similarity, the targets in the contiguous condition (5 and 6) share five line segments with one left over, and the targets in the separated condition (5 and 9) also share five line segments with one left over so target shape similarity was the same in both conditions. While the results from Experiment 2 are consistent with both target grouping by contiguous number line position and grouping by shape similarity, the results from Experiment 3 are consistent only with target grouping by contiguous number line position.

In Experiments 1, 2, and 3 search was faster when targets were contiguous than when they were not, but we hypothesized that both target contiguity and coherence would make search easier. Because in Experiment 3 we manipulated target contiguity while holding target coherence fixed, the next logical step would be to manipulate target coherence while holding target contiguity fixed (and also, as in Experiment 3, holding distractor set fixed in order to eliminate distractor grouping as an alternative explanation). However, manipulating target coherence while holding target contiguity and distractor set fixed makes it impossible to control target-distractor linear separability and numerical distance. As can be seen by inspecting the upper portion of Fig. 5, to manipulate target coherence while controlling target contiguity and distractor set, the targets must be linearly separable and relatively distant from distractors in the coherent condition, and not linearly separable and relatively near distractors in the non-coherent condition. As a result all three hypotheses (target coherence, target-distractor linear separability, and target-distractor numerical distance) make the same prediction: search should be easier in the coherent/linearly separable/numerically distant condition. Although this experiment cannot dissociate between the influence of these three aspects of number line relationships on search, it is nevertheless useful for verifying the single prediction made by all three hypotheses.

Experiment 4: Coherent vs. non-coherent targets

Method

Experiment 4 was similar to the previous experiments, with the following exceptions.

Participants A total of 28 undergraduate students from the University of Central Arkansas volunteered for the experiment in exchange for class credit. None had participated in the previous experiments. Participants were randomly assigned to one of two grouping conditions.

Stimuli Participants in the coherent targets condition searched for the targets 5 and 9 among the distractors 3 and 4, and in the non-coherent targets condition searched for the targets 2 and 6

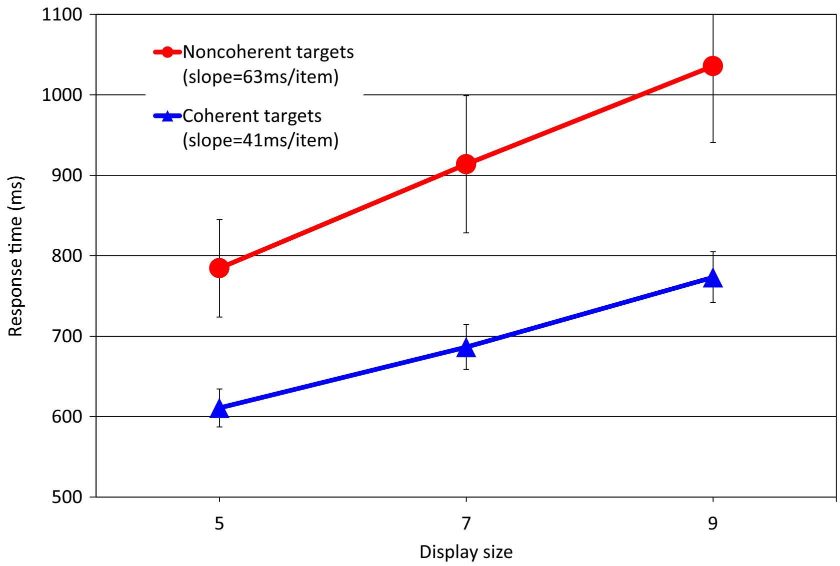

Fig. 5 Number line positions of target and distractor digits in Experiment 4 (target digits are enclosed by a box) and RTs as a function of display size. Error bars indicate standard errors of the means

among the distractors 3 and 4. In both conditions the distance between targets was the same (9 – 5 = 6 – 2 = 4) but only in the non-coherent condition were the distractors situated between the targets on the number line.

Procedure The procedure was identical to that in Experiment 3.

Results and discussion

Mean correct RTs (depicted in Fig. 5) were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. The main effects of grouping condition, $F(1, 26) = 6.96$, $p = .014$, $\eta^2 = .211$, display size, $F(2, 52) = 72.9$, $p < .001$, $\eta^2 = .712$, and the interaction, $F(2, 52) = 3.42$, $p = .040$, $\eta^2 = .0334$, were significant. A t-test comparing slopes with grouping condition as a between-subjects variable was marginally significant, $t(26) = 2.01$, $p = .054$, $\eta^2 = .136$. Mean error rates were submitted to a 2 × 3 ANOVA with grouping condition as a between-subjects variable and display size as within-subjects. No effects were significant, and error rates were not further analyzed.

Search was faster and more efficient in the coherent condition, in which (1) there were no distractors between targets on the number line, (2) the targets were linearly separable from distractors, and (3) the target-distractor distance was larger (mean numerical distance between every pair of targets and distractors = 3.5) than in the non-coherent condition (mean numerical target-distractor distance = 2). In addition, the target shapes were more similar in the coherent condition, suggesting that targets could be more easily grouped by shape: by Cohen's (2009) metric of physical similarity, the targets in the coherent condition (5 and 9) share five line segments with one left over (5/1 = 5), and the targets in the non-coherent condition (2 and 6) share four line segments with two left over (4/2 = 2). However, the results could not be explained by brightness differences because the targets had the same number of line segments and were therefore equally bright in both conditions. While the results from Experiment 4 do not allow us to isolate the contributions of target coherence from target-distractor linear separability, target-distractor numerical distance, and target shape similarity, they are valuable insofar as a failure to obtain these results would have undermined our interpretations from the previous experiments.

General Discussion

Uncovering the role of semantic associations in visual search for alphanumeric characters has always been a tricky business, primarily due to the difficulty of eliminating visual confounds from semantic manipulations (Krueger, 1984; Wolfe & Horowitz, 2004). Using a limited character set (þ, B, b, and p) to control the contributions of shape, Lupyan (2008) showed that search performance improves with distractor-distractor similarity. Schwarz and Eiselt (2012) also limited their character set by using a single target digit, and discovered that search performance improves with target-distractor numerical distance. Godwin et al. (2014) showed that a broader character set could be used provided the experimenter uses a metric of shape similarity to control the role of shape. We built on these studies with an eye to visual search experiments with multiple targets in which search performance improves with target-target perceptual similarity (Menneer et al., 2009;

Stroud et al., 2012), and used a metric of shape similarity (Cohen, 2009) to control the contributions of shape.

We hypothesized that the visual search performance for multiple target digits should improve with target contiguity and coherence on the number line. The results from four experiments were all consistent with our hypothesis. Search performance was better when the target group was both contiguous and coherent than when the target group was neither contiguous nor coherent (Experiments 1 and 2), when the target group was contiguous and coherent than when the target group was not contiguous but was coherent (Experiment 3), and when the target group was coherent but not contiguous than when the target group was neither contiguous nor coherent (Experiment 4). In addition, we considered four alternative explanations for our results, two of them (like ours) based on the arrangement of targets and distractors on the number line (linear separability of targets from distractors and target-distractor numerical distance), and two based on perceptual features (similarity of target shapes and target brightness). By carefully selecting the target and distractor shapes and number line positions in Experiments 2 through 4, we showed that target-distractor linear separability and numerical distance could not have contributed to the results in Experiments 2 or 3, target shape similarity could not have contributed to the results in Experiment 3, and target brightness could not have contributed to Experiments 2, 3, or 4.

Target-distractor numerical distance for multiple targets

For each of the alternative explanations that we considered, we were generally either able to control for the alternative explanation or our results were consistent with the alternative explanation. A notable exception was Experiment 3 in which search performance improved with target contiguity (5 and 6 are contiguous whereas 5 and 9 are not) as predicted by our hypotheses, but this result entailed that search performance improved with target-distractor numerical proximity (5 and 6 are nearer to 3 and 4 than 5 and 9), in the opposite direction to what would be predicted by the target-distractor numerical *distance* account (Schwarz & Eiselt, 2012; Godwin et al., 2014). This result implies either that in Experiment 3 the effect of target contiguity was more robust than the effect of numerical distance, or that there was no effect of numerical distance for target contiguity to fight against.

The most salient difference between our experiments and those that have found an effect of target-distractor numerical distance (Schwarz & Eiselt, 2012; Godwin et al., 2014) is that our experiments used multiple targets. Working memory has been implicated as critical for efficient visual search (Anderson, Vogel, & Awh, 2013; Poole & Kane, 2009; Sobel, Gerrie, Poole, & Kane, 2007), perhaps by, among other things, maintaining a target template and comparing candidate items to the template (Beck, Hollingworth, & Luck, 2011; Olivers, Peters, Houtkamp, & Roelfsema, 2011). A search for multiple targets should require a more complex target template in working memory than a search for a single target. Perhaps maintaining a complex target template in working memory interferes with the ability to consider the numerical distance between the distractors and both possible targets, and instead participants considered just the numerical distance between the distractors and the nearer of two targets. Because the target that was nearer to the distractors was the same in both conditions (5 is nearer to 3 and 4 than 6 as in the contiguous condition and 5 is nearer than 9 as in the discontiguous condition), such a strategy would eliminate the difference in target-distractor numerical distance.

Automaticity of semantic activation in visual search

We and other researchers who have controlled for perceptual similarity (Godwin et al., 2014; Lupyan, 2008; Schwarz & Eiselt, 2012) have gathered evidence that characters' semantic associations are sufficient to drive salient differences in behavior. In contrast, other researchers (Cohen, 2009; García-Orza et al., 2012) have argued that effects that seem to be driven by semantic associations are better explained in terms of perceptual features. A reconciliation between the two accounts may hinge on whether alphanumeric characters automatically elicit the semantic associations they represent. Tzelgov and Ganor-Stern (2005) suggested that a diagnostic test for automaticity of semantic activation is that it occurs even in tasks for which it is irrelevant for completion of the task. The paradigm case of automaticity is the Stroop (1935) effect in which participants attempt to name the ink color of printed words. The meanings of the words are irrelevant to completing the task and yet they interfere with color naming, indicating that these words automatically activate the colors associated with them.

In contrast to words, Goldfarb, Henik, Rubinsten, Bloch-David, and Gertner (2011) argued that numbers do not automatically activate the numerical quantity they represent; to activate a number's semantic component there must be some aspect of the task that triggers it. For example, number comparison tasks for which numerical quantity is intrinsic (e.g., Does this digit have a bigger or smaller numerical magnitude than the target digit?) are likely to elicit a numerical distance effect, whereas tasks for which numerical quantity is not intrinsic as in Cohen (2009) and García-Orza et al. (2012) (e.g., Is this digit the same as or different than the target digit?) can be completed strictly on the basis of shape.

The finding that viewing numbers does not automatically activate their associated numerical quantity (Goldfarb et al., 2011), together with the results from our study and others (Godwin et al., 2014; Lupyan, 2008; Schwarz & Eiselt, 2012) that showed effects of numerical processing on visual search, imply that numerical processing must somehow be beneficial to task performance in visual search. If so, how? The results from a visual search experiment for which search items were 90° rotations of digital clockface 2s and 5s (Lupyan & Spivey, 2008) may provide the key. In this study search performance was better for participants who were informed that the stimuli were rotated versions of digits than for participants in the uninformed condition, suggesting that it is easier to maintain a numerical character in the target template when the semantic association is included along with the character's shape. We predict that search for multiple target digits should strongly activate their semantic associations because grouping them by their number line positions should produce a more concise representation of the collection of numbers than their respective shapes.

Extending the number line to two-digit numbers

The present study and others (Godwin et al., 2014; Krueger, 1984; Lupyan, 2008; Schwarz & Eiselt, 2012) that have investigated the role of semantic associations on visual search all used search items composed of single characters, so it is tempting to ask how the inclusion of two-digit items within the set of search items would impact observed number line effects. In numerical comparison tasks that find a numerical distance effect (Goldfarb et al., 2011; Moyer & Landauer, 1967), RT commonly increases with the proximity between the two items to be compared, presumably because the nearer two items are, the more difficult they are to distinguish from each other. Pinhas et al. (2013) presented two digits at a time selected from either a relatively narrow (i.e., 11–19) or wide (i.e., 11–39) range and asked participants to make a numerical judgment about the two digits. For a given numerical distance, RTs were longer in the wide range condition. The authors argued that both the wide and narrow numerical ranges had to be fit into the same mental space so the numerical distance between digits was correspondingly smaller in the wide range condition than in the narrow range condition. By extension, we expect that for visual searches that include search items in the two-digit range, numerical distances would be reduced. Consequently, distinguishing targets from distractors should be more difficult, whereas for a given numerical distance between them, target-target and distractor-distractor grouping should be easier.

Here we focused on how number line contiguity and coherence of targets influence visual search performance, and demonstrated an advantage for target digits that are more easily grouped along the number line. The techniques that we pioneered should facilitate further investigations into semantic influences on visual search for numbers, such as interactions between target grouping and distractor grouping, the effect of including numbers consisting of more than one digit, and, more generally, discovering what aspects of visual search trigger the activation of semantic associations.

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