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The rapid extraction of numeric meaning

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Abstract

Several kinds of statistical properties can be rapidly extracted from visual displays (e.g., luminance and roughness, Olive, A., & Torralba, A. (2001). Modeling the shape of the scene: a holistic representation of the spatial envelope. *International Journal of Computational Vision, 42*, 145–175). Here, we investigate whether this phenomenon extends to meaning contained in Arabic numerals. Observers were shown brief displays containing two sets of numerals and asked to determine which contained the largest average value. Comparisons were made more quickly and accurately between displays of digits than between displays of letters and shapes; this effect could not be attributed to task instructions. When numeric meaning could be used in a classification task, performance was better for digits than for letters, but when numeric meaning could not be used as a basis of classification, performance was approximately equal across stimulus types, suggesting that numeric meaning is rapidly extracted only when it is task-relevant. The digit advantage was eliminated with unlimited viewing time, suggesting that this process is used when counting is not possible. Dual-task methodology revealed that this process requires limited-capacity attentional resources.

Keywords: Attention; Numeric meaning; Rapid extraction

1. Introduction

A growing body of evidence suggests that the visual system does not represent all visible objects and that our perceptions are formed using a limited amount of visual input (Irwin, 1991; Simons & Levin, 1998; but see Simons & Rensink, 2005). How might the visual system create an illusion of a composite perceptual image, despite this evidence that a limited amount of the dynamic environment is actually represented? Hochberg (1978) and Hock and Schmelzkopf (1980) proposed that we abstract a conceptual representation of a scene from several successive fixations. Ariely (2001) and Ariely and Burbeck (1995) further suggested that our perceptions may be generated from occasional detailed samples, together with statistical summaries of remaining areas, and an overall interpretation of the meaning or gist.

Several studies support the notion that our perceptions are formed by conceptually integrating a limited amount of visual information over successive views. In a study of transsaccadic memory, Irwin (1991) asked observers to view a random dot pattern during one fixation and then to determine whether a second dot pattern, presented in the successive fixation, was identical to the first pattern. He found that participants could not reliably determine whether the two patterns were identical. In addition, other experiments have shown that changing visual characteristics of words, such as letter case, does not disrupt reading or naming of the word (McConkie & Zola, 1979; Pollatsek, Rayner, & Collins, 1984). If visual processing relies on a composite representation, such changes across eye movements or in visual characteristics should have been easily detected and should have had a disruptive effect on perception.

Findings from change blindness studies also indicate that the visual system represents a limited amount of information. In a classic demonstration (Simons & Levin, 1998),

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an experimenter approached a pedestrian to ask for directions. While the participant was giving directions to the experimenter, two confederates carrying a door walked between them. During this brief interruption, a different person replaced the original experimenter. Even though the two experimenters looked and sounded very different, about half of the participants failed to notice that they were talking to a different person after the door passed. Such failures to detect large and meaningful changes demonstrate that, at least under some circumstances, a limited amount of information is consciously available for forming visual representations.

Barlow (1961) hypothesized that sensory neurons remove statistical redundancy in sensory input during early stages of visual processing. It is widely agreed that such neurons appear to have adapted to extract the statistical properties of the sensory information to which they are exposed (Olshausen & Field, 1996; Simoncelli & Olshausen, 2001). For example, several studies have found evidence that the visual system represents structural properties of images, such as sparseness, roughness, and luminance, using statistical coding (Baddeley, 1997; Kersten, 1987; Oliva & Torralba, 2001). Torralba and Oliva (2003) asked observers to determine whether an object from a given category (e.g., animal, building, or vehicle) was present or absent in a briefly presented display based only on categorically averaged second-order image statistics such as luminance and roughness (image average). Observers were well above chance at determining the presence or absence of the given object based on its corresponding image average. Taken together, these findings suggest that the visual system may use such characteristic image statistics to rapidly represent visual objects.

The visual world is highly redundant, containing many similar objects with fairly uniform properties (e.g., leaves on a tree, clouds in the sky, or a shelf of books). Ariely (2001; see also Ariely and Burbeck, 1995) proposed that, when presented with similar items, the visual system rapidly creates a representation of the statistical properties of the set and discards information about the individual items within the set. Ariely (2001) conducted an experiment to test this possibility using two tasks, a member identification task and a mean discrimination task. Each trial consisted of a set of circles of different sizes in the first interval and an image of a single circle (drawn from within the size range of the first interval set) in the second interval. In the member identification condition, the task was to report whether the single circle was a member of the first interval set. In the mean discrimination condition, the task was to report whether the single circle was larger or smaller than the mean circle size of the first interval set. In the member identification condition, observers could not reliably distinguish the size of the individual circle and could not accurately indicate whether the single circle was a member of the set. In contrast, in the mean discrimination condition, observers were highly accurate in determining whether the size of the single circle was equal to the mean size of the first set of circles. From these results, Ariely suggested that the visual system creates a statistical representation of the set, not including precise information about the individual items. Chong and Treisman (2003) demonstrated that participants were equally fast and accurate when judging which of two side-by-side displays of circles of heterogeneous sizes had the larger mean size as they were at determining which of two displays of homogeneous circles had the larger mean size, or which of two single circles was larger. This suggests that the mean judgment was at least as fast and accurate as comparing individual items. Further work by Chong and Treisman (2005b) has shown that there is no effect of numerosity or density on the rapid averaging process, but that items can first be grouped by a property such as color. This suggests that the mean size of a group of items can be computed automatically and in parallel after an initial preattentive segregation by a salient group feature such as color or orientation.

In addition to mean size, other stimulus properties may be statistically represented. For example, observers are poor at judging the mean orientation of a small number of Gaussian distributed orientations, but as the number of orientations is increased, accuracy for the mean judgment is markedly improved, suggesting that visual texture information is statistically represented (Dakin & Watt, 1997). Observers can also accurately estimate the mean orientation of several Gabor patches but cannot report the orientation of individual patches (Parkes, Lund, Angelucci, & Morgan, 2001). Participants can distinguish the mean direction of motion among various moving stimuli but cannot describe the direction of motion for individual stimuli (Watamaniuk, Sekuler, & Williams, 1989).

Results from visual search studies support the possibility of rapid, parallel comparisons for categorically dissimilar items (e.g., a letter target among digits; Egeth, Jonides, & Wall, 1972), whereas search for categorically similar items is a linearly increasing function of set size (Atkinson, Holmgren, & Juola, 1969). These results suggest that conceptual discrimination may be a separate and more efficient process than character identification (Brand, 1971; Posner, 1970). Further support for this proposal comes from classic visual search work by Jonides and Gleitman (1972). They asked participants to detect a digit or letter target in a field of digits or letters. Consistent with past results, they found that when the target and field category (digits/letters) differed, reaction times were independent of display size, whereas when the target and field were from the same conceptual category, reaction time was an increasing linear function of set size. Of particular interest was the finding that the conceptually ambiguous item "0" was processed in relation to how it was specified prior to the experiment, as "zero" or "oh." For example, an "oh" was found to "pop-out" from a field of digits but a "zero" did not, even though both were represented by the same stimulus, "0." Because categorical meaning could be specified by task instructions, this study strongly suggested that recognition takes place at the level of conceptual category (stimulus type) rather than at the level of physical characteristics (individual stimuli), although it has not been consistently replicated (Duncan, 1983; Krueger, 1984).

Several studies suggest that numeric information is rapidly (or perhaps even automatically) extracted from digits. For example, Henik and Tzelgov (1982) found that participants were able to determine more quickly which of two digits was physically larger when the physically larger digit was also the numerically larger digit. Also, Dehaene and Akhavein (1995) found that participants made more errors when judging two stimuli as physically different when the quantities represented by the two stimuli were equal (e.g., TWO and 2) than when they were unequal (e.g., TWO and 4). Finally, Windes (1968; see also Pavese and Umiltà, 1998) showed that participants were faster when reporting the number of items present in displays of symbols (e.g., three plus signs) vs. displays of digits (e.g., three ones). Three threes, however, led to faster response times than three letters, suggesting both interference and facilitation from irrelevant numeric information. Taken together, these studies suggest that information about a digit's magnitude is automatically accessed, even when it is detrimental to performance.

Previous research therefore suggests that (i) the visual system uses processing shortcuts to rapidly represent properties of a scene and (ii) numeric information (magnitude information) is automatically processed. This study therefore examined whether task-relevant numeric information can also be processed rapidly, or at least, more rapidly than task-irrelevant information about familiarity or shape. Participants were presented with displays of digits, letters, or shapes. In Experiment 1, when viewing displays of digits, participants reported which side of the display had the larger average value. In the letter displays, participants reported which side of the display had the greater occurrence of a target letter. In the shape displays, participants reported which side had the greater occurrence of a target shape. In Experiment 2, task instructions were equated across display types to ensure that the observed digits advantage could not be attributed to differences in instructions across conditions. Experiment 3 determined that the advantage for digits was eliminated when numeric meaning was not task-relevant. In Experiment 4, viewing time for the displays was unlimited and the advantage for digits again disappeared. Finally, Experiment 5 used the psychological refractory period (PRP) paradigm to determine whether the process responsible for rapidly extracting numeric meaning of digits requires central processing resources.

2. Experiment 1

Building upon previous research demonstrating that the visual system can rapidly extract overall spatial and statistical properties of a scene, Experiment 1 investigated whether this was also true of numeric value. Participants were asked to make comparisons between sets of meaningful familiar digits (2's and 5's), familiar letters (p's and q's), or simple shapes (these same stimuli, rotated by 90°). If numeric meaning is extracted faster and more accurately than information about familiarity or shape, then participants should be able to make comparisons more quickly and accurately between digits than between letters or shapes. To ensure that differences in spatial arrangement or symmetry were not the basis of any observed advantage for digits over the other types of stimuli, the sets of items in Experiment 1 included digits and letters rotated by 90° to the left, which maintained the spatial relations of the upright digits and letters. If numeric meaning is the basis for better performance for digit comparisons than for comparisons between the other types of items, then rotating digits sideways should cause the numeric meaning and familiarity of the digits to be lost, and rotating letters sideways should eliminate the familiarity of the letters. Therefore, if numeric meaning facilitates comparisons between items in the displays, this advantage should be eliminated when the digits are rotated, and rotation should have a greater effect on comparisons between digits than on comparisons between letters. To investigate possible differences in processing over time, stimuli were presented at three durations: 80, 200, and 650 ms.

2.1. Method

2.1.1. Participants

Nine University of British Columbia undergraduates participated in Experiment 1. Participants received two extra credits in a psychology course or $10 in exchange for their voluntary participation. All had normal or corrected-to-normal vision.

2.1.2. Apparatus and stimuli

In Experiments 1–4, stimuli were presented on eMAC computers, which also performed all timing functions and recorded participants' responses. Participants viewed the screen with both eyes from approximately 60 cm. The eight individual stimuli were block character digits, letters, and shapes. Each of the digit and letter stimuli were mirror images of one another and subtended approximately $0.75° \times 0.25°$ visual angle. Each shape stimulus (rotated digits and letters) subtended approximately $0.25° \times 0.75°$ visual angle. In all experiments reported here, only 2's, 5's, p's, and q's were used as digit and letter stimuli. We chose these particular stimuli because they share vertical symmetry and shape similarities, helping to rule out these factors as alternative explanations for any observed advantage. Research has shown that rotated alphanumeric stimuli are processed as such, unless they must be discriminated from a mirror-reversed counterpart (Koriat & Norman, 1984; Simion, Bagnara, Roncato, & Umilta, 1982). In the case of mirror-image alphanumeric stimuli, a mental rotation is required. Using digit and letter stimuli that were mirror images of one another helped to ensure that participants were processing the rotated digit and letter stimuli as shapes and not as digits or letters, respectively. Shapes were

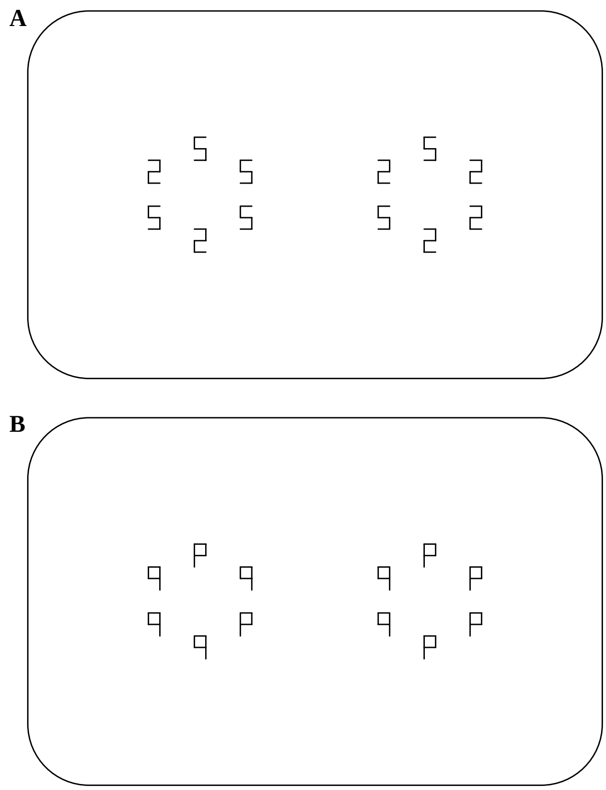

Fig. 1. Examples of the digit (A) and letter (B) displays used in Experiments 1, 2, and 4.

made by rotating the digits and letters 90° to the left, creating sideways digits and sideways letters. Each display was divided vertically into two halves, each half containing a radial array of six items. Radial arrays subtended approximately 4° visual angle, with individual stimuli separated by an average of 1°. The arrays were vertically centered on the screen and separated from central fixation by an average horizontal distance of 2.25°. Both halves of the screen contained the same stimulus type (digit, sideways digits, letters, or sideways letters). Examples of the displays used in Experiments 1, 2, and 4 are shown in Fig. 1.

2.1.3. Sequence of events

Each trial began with a 100 ms fixation cross in the center of the screen, signaling that the stimulus display was about to appear. After the offset of the fixation cross, the stimulus display was shown for 80, 200, or 650 ms, followed by a blank screen until the participant responded. After responding, the participant was given feedback in the center of the screen. A "+" was displayed for a correct response, and a "−" was displayed for an incorrect response.

2.1.4. Task

When viewing displays of digits, participants had to indicate which side of the display had the larger average value. When presented with displays of letters, the participants' task was to indicate which side of the display had the larger number of "q's," and when viewing displays of shapes, participants were required to indicate which side had the more frequent occurrence of a target shape (⊔⊓ or ⊏⊤). Participants were instructed to compare the displays as quickly and accurately as possible.

2.1.5. Design

Each of the four display types (digits, sideways digits, letters, and sideways letters) was presented at each of three durations (80, 200, and 650 ms), for a total of 12 conditions. Each condition contained 48 trials in which the left array had the larger average value or the greater occurrence of the target and 48 trials that were the mirror images of these in which the right side of the display had the larger average value or the greater occurrence of the target. Each trial was shown twice in each condition for a total of 192 trials per condition. The order of conditions was counterbalanced across participants. The 192 trials in each condition were divided randomly into four blocks of 48 trials. Before beginning each condition, participants were given as many practice trials as needed to be able to understand the task.

2.2. Results

Two dependent variables were measured in all experiments: reaction time and accuracy. In all experiments, only correct responses were considered in reaction time analyses. To examine the effects of numeric meaning and stimulus duration, the results of Experiment 1 were first analyzed using repeated-measures ANOVAs that examined the within-participant factors of display type (digits, sideways digits, letters, or sideways letters) and stimulus duration (80, 200, or 650 ms) for reaction time and response accuracy, respectively. As shown in Figs. 2A and B, respectively, comparisons between digits were made more quickly and accurately than comparisons between other types of stimuli. This pattern led to a significant main effect of display type on reaction time, $F(3,24) = 9.264$, $MSE = 14{,}117$, $p < .001$, and accuracy, $F(3,24) = 10.789$, $MSE = .0019$, $p < .001$. There was no main effect of stimulus duration on either reaction time or accuracy, and there was no interaction between the two factors.

To test for a specific advantage for comparisons made between items in digit displays, for each participant the mean reaction time for digit displays was compared to the average of the mean reaction times for the remaining three display types (sideways digits, letters, and sideways letters). This comparison was also made for response accuracy. Digits were processed faster, $t(8) = -7.468$, $p < .001$, and more accurately, $t(8) = 6.136$, $p < .001$, than the other three display types. On average, participants required 484 ms to respond correctly to digit displays and were 87% accurate in doing so. Table 1 shows the mean reaction times and accuracy for each exposure duration of the four display types in Experiment 1.

To determine the contribution of numeric meaning further, the effect of rotation for digits and letters was

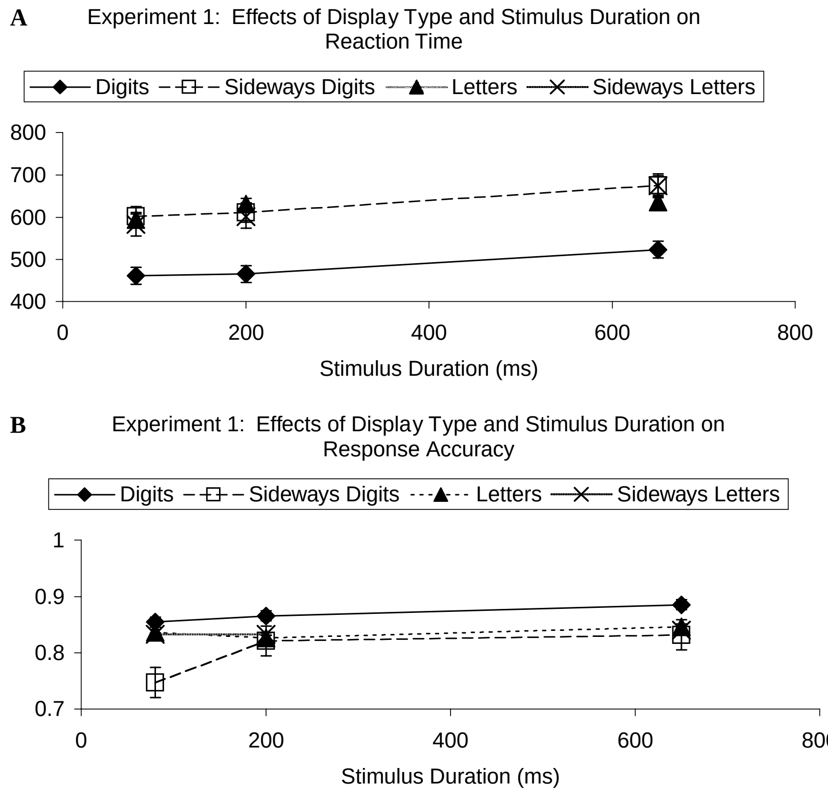

Fig. 2. Experiment 1 ($n = 9$): psarticipants compared digits displays faster (A) and more accurately (B) than displays of sideways digits, letters, or sideways letters. However, there was no effect of stimulus duration on reaction time (A) or accuracy (B). Error bars represent one standard error.

Table 1
Experiment 1 ($n = 9$): mean reaction time (ms) and accuracy (parentheses) for each display type

Stimulus duration (ms)	Digits	Sideways digits	Letters	Sideways letters
80	461 (.85)	602 (.75)	595 (.84)	583 (.83)
200	466 (.87)	611 (.82)	631 (.83)	602 (.83)
650	523 (.89)	675 (.83)	636 (.85)	674 (.84)

analyzed using a second set of repeated-measures ANOVAs that examined the within-participant factors of stimulus type (digits, letters) and rotation (upright, sideways) on reaction time and accuracy. The analysis revealed a main effect of rotation on reaction time, $F(1,8) = 8.65$, $MSE = 47{,}027$, $p < .05$, and accuracy, $F(1,8) = 15.5$, $MSE = .0007$, $p < .05$, such that upright stimuli were processed faster than rotated stimuli. More importantly, rotation impaired performance more for digits than for letters, leading to a significant interaction between stimulus type and rotation on reaction time, $F(1,8) = 20.609$, $MSE = 49{,}045$, $p < .005$, and accuracy, $F(1,8) = 22.450$, $MSE = .0005$, $p < .001$.

2.3. Discussion

The goals of Experiment 1 were to determine whether numeric information could be used to facilitate performance in a comparison task and to determine whether there were any differences between how digits and the other displays types were compared over time. The main effect of display type and the paired comparison between the digits condition and the average of performance in the other three display type conditions showed that comparisons between digits were made more quickly and accurately than comparisons between items in the other three display types. Reaction times and accuracy for sideways digits did not differ from letters and sideways letters, and were slower and less accurate than comparisons between digits, confirming that differences in spatial arrangement or symmetry were not the basis of the observed digits advantage.

It is important to note that display types varied from each other in three aspects: numeric meaning, familiarity, and shape. Digits have numeric meaning, are familiar, and have similar shapes. In principle, any of these attributes could be the basis for rapid processing. Letters, in contrast, are familiar and have shape similarities but no numeric meaning. Similarly, sideways digits and sideways letters have shape similarities but lack both familiarity and numeric meaning. Therefore, the advantage for digits over the other three display types must be attributed to numeric meaning, which was lost when these very same items were rotated, leading to performance that was similar to that observed for comparisons between letters and rotated letters.

A final question was whether the process responsible for rapidly extracting numeric information behaved differently over time than the processes responsible for processing familiar letters or simple shapes. The lack of a main effect or any interactions with stimulus duration for reaction time or accuracy suggest that there are no differences in how each display type is processed over time as a function of manipulating exposure duration over a range of brief durations.

An advantage in both reaction time and accuracy was observed for digits displays that could not be attributed to familiarity or to a specific configuration of features unique to digits. Rotating the digits by 90° eliminated the digit advantage. This suggests that there is an advantage for making quantitative comparisons between displays of digits because they have numeric meaning. Therefore, the most important result of Experiment 1 was that numeric information facilitated quantitative comparisons between displays of items.

3. Experiment 2

From the results of Experiment 1, it was unclear whether it was numeric meaning itself or the instruction to compare digit displays based on average numeric value that led to faster and more accurate comparisons. The controversial finding of Jonides and Gleitman (1972) that an ambiguous stimulus could be processed faster if it was defined as conceptually different from a field of distractors than if it was defined as conceptually similar suggests that conceptual meaning can be specified by task instructions. The faster and more accurate processing of digit displays found in Experiment 1 may also have been due to a difference in task instructions between the display types, namely the instructions to compare digits based on average value and to compare letters and shapes based on frequency of occurrence (Chong & Treisman, 2003). Experiment 2 was conducted as a control experiment to determine whether the rapid digit processing found in Experiment 1 was due primarily to the instructions to compare the average value of digit displays (as opposed to the more frequent occurrence of a target shape in the other three conditions). Participants in Experiment 2 were told to compare all display types based on the more frequent occurrence of a target shape. In addition, if the instruction to compare the average value of digit displays led participants to interpret the digits as meaningful stimuli within the context of the task when they would not have done so in the absence of this instruction, then equating the task instructions across display types should eliminate the advantage for digit displays in Experiment 2.

3.1. Method

3.1.1. Participants

Twelve University of British Columbia undergraduates participated in Experiment 2 in exchange for two extra credits in a department psychology course or monetary compensation ($10). All had normal or corrected-to-normal vision.

3.1.2. Task

Experiment 2 was identical to Experiment 1 in all respects with the exception of the task instructions concerning digit displays. Instead of deciding which digit display had the larger average value or which letter or shape display had the greater occurrence of a target character, participants were instructed for all displays to indicate which display contained the greater occurrence of a character (now Ϛ for digit displays).

3.2. Results

To determine whether numeric meaning was imparted to the digit stimuli by the nature of the experimental task or specified by task instructions, the results of Experiment 2 were compared to those of Experiment 1. The average mean reaction time and accuracy for each display type and stimulus duration in Experiment 2 are listed in Table 2. Analysis of the combined data from Experiments 1 and 2 revealed no significant main effects of task instructions on reaction time or accuracy. Furthermore, ANOVAs comparing the within-participant factors of display type and stimulus duration in Experiment 2 showed that there was again a significant main effect of display type on reaction time, $F(3,33) = 9.573$, $MSE = 14{,}878$, $p < .001$, and accuracy, $F(3,33) = 9.983$, $MSE = .04$, $p < .001$, but no effect of stimulus duration on reaction time. Accuracy increased with increasing exposure duration, leading to a significant main effect of stimulus duration, $F(2,22) = 5.24$, $MSE = .003$, $p < .02$. Again digits were processed faster, $t(11) = 5.99$, $p < .001$, and more accurately, $t(11) = -5.21$, $p < .001$, than the average mean reaction time and accuracy of the other three display types over all stimulus durations (Figs. 3A and B, respectively). A second set of ANOVAs compared the within-participant factors of stimulus type (letter or digit) and rotation. Consistent with Experiment 1, digits and upright stimuli were processed more quickly than letters and rotated stimuli, leading to significant main effects of stimulus type, $F(1,11) = 350.2$, $MSE = 48{,}843$, $p < .001$, and rotation, $F(1,11) = 121.5$, $MSE = 5377$, $p < .001$, on reaction time. Responses to upright stimuli tended to be more accurate than responses to rotated stimuli, leading to a marginally significant main effect of rotation, $F(1,11) = 11.5$, $MSE = .003$, $p < .06$, on accuracy. Also consistent with Experiment 1, and most importantly, rotation impaired performance more for digits than for letters, leading to a significant interaction between display type and rotation

Table 2
Experiment 2 ($n = 12$): mean reaction time (ms) and accuracy (parentheses) for each display type

Stimulus duration (ms)	Digits	Sideways digits	Letters	Sideways letters
80	504 (.87)	648 (.77)	630 (.83)	605 (.79)
200	488 (.87)	630 (.79)	582 (.83)	593 (.80)
650	532 (.88)	686 (.83)	620 (.84)	648 (.84)

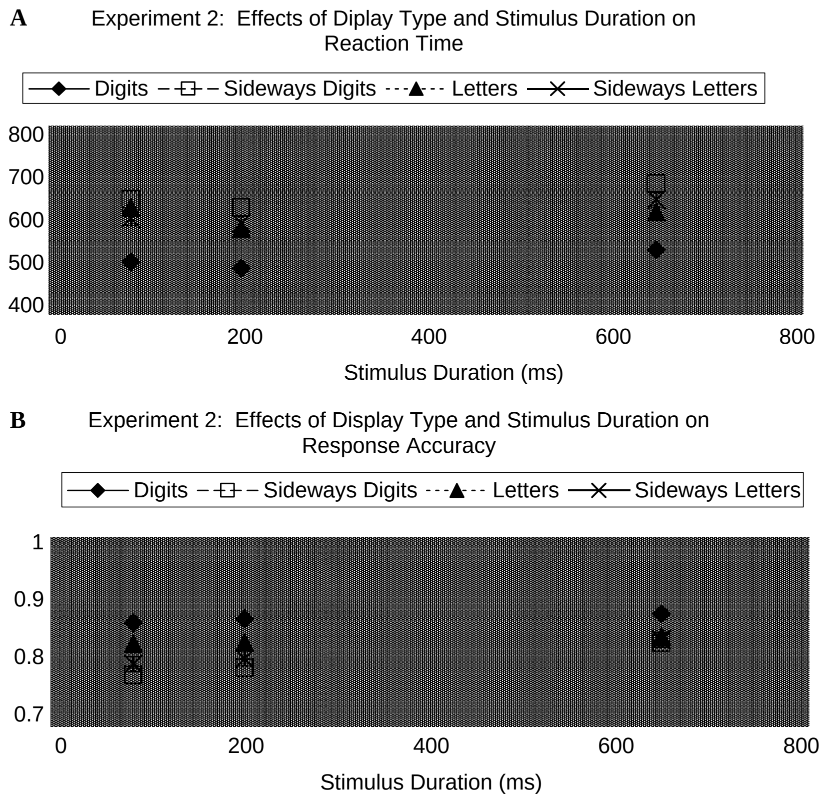

Fig. 3. Experiment 2 ($n = 12$): as in Experiment 1, participants in Experiment 2 compared digits displays faster (A) and more accurately (B) than displays of sideways digits, letters, or sideways letters. There was no effect of stimulus duration on reaction time (A) or accuracy (B). Error bars represent one standard error.

on reaction time, $F(1,11) = 188.1$, $MSE = 4778$, $p < .001$, and on accuracy, $F(1,11) = 17.9$, $MSE = .005$, $p < .001$.

3.3. Discussion

Changing the instructions did not affect how participants compared digit displays. The experiments differed only in task instructions for digit displays, yet produced identical results. Contrary to the results of Jonides and Gleitman (1972), which suggested that conceptual meaning could be assigned to stimuli by task instructions, participants compared digits faster and more accurately than the other display types regardless of whether numeric meaning was specified by task instructions (“Report the side with the larger average value”; Experiment 1) or not (“Report the side with the greater frequency of the target shape”; Experiment 2). Therefore, the numeric meaning unique to digits in this task appears to have led to the observed advantage of comparisons between digits, rather than the instruction to compare digits based on average value, or differences in task instructions across conditions in Experiment 1.

4. Experiment 3

The results of Experiments 1 and 2 suggested that the numeric meaning unique to digit displays was driving the digits advantage because numeric meaning was relevant to the quantitative comparison task, whereas no such basis for comparison existed for displays of letters or shapes. To test directly whether task relevance was the critical factor leading to the observed digits advantage in the preceding experiments, Experiment 3 compared performance on two tasks; one task in which numeric meaning was relevant and one task in which it was not. If the task relevance of the digits in the previous experiments allowed participants to use the average value (numeric meaning) to facilitate the quantitative comparisons of digit displays, then this advantage should not be found for a task in which numeric meaning is not relevant. In other words, when numeric meaning is task-relevant, participants should perform better on digit displays than on letter displays, but when numeric meaning is not task-relevant, performance should be equal for digit displays and letter displays.

4.1. Method

4.1.1. Participants

Forty-two University of British Columbia undergraduates participated in Experiment 3 in exchange for one extra credit in a department psychology course. All had normal or corrected-to-normal vision.

4.1.2. Design and task

In Experiment 3, participants were shown the same individual digits and letters as in Experiments 1 and 2.

However, in Experiment 3, a single radial display of six digits or letters was presented for 100 ms at fixation (Fig. 4). Instead of deciding which of two displays had more of a given target, participants in Experiment 3 were given 2000 ms to perform one of two tasks. In the same/different task, participants had to judge whether all items in a digit or letter display were homogeneous. For example, when shown a radial display of five "p's" and one "q," a participant would respond correctly by indicating that the displays contained "different" items, and when shown a display of six "5's," a participant would respond correctly by indicating that the display contained elements that were all the "same." In this task, participants pressed the "z" key if all the items in the display were the same and the "?" key if any of the items in the display were different. In the more/less task, participants were required to determine which of two stimuli appeared more frequently in the display. For example, when shown a display of four "5's" and two "2's," a participant would respond correctly by indicating that there were more "5's" in the display. Participants pressed the "z" key if there were more "2's" or "q's" in the display and they pressed the "?" key if there were more "5's" or "p's" in the display. Participants performed each task (same/different or more/less) for each stimulus type (digits and letters) for a total of four conditions with four blocks of 48 trials in each. The order of conditions was counterbalanced across subjects. Participants were given practice trials before the start of each block until they could achieve 85% accuracy.

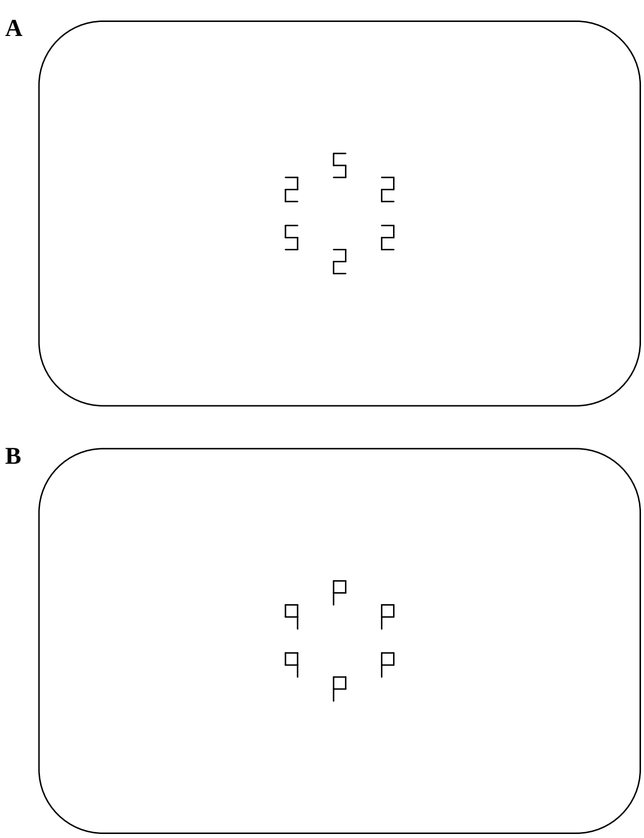

Fig. 4. Examples of the digit (A) and letter (B) displays used in Experiments 3 and 5.

4.2. Results

The mean reaction time and accuracy for each display type and stimulus duration in Experiment 3 are listed in Table 3. A repeated-measures ANOVA with the within-participants factors of display type (digits vs. letters) and task (same/different vs. more/less) was used to analyze mean response times for each subject in each condition. We argued that comparisons between digits were made more quickly than comparisons between letters and shapes in Experiments 1 and 2 because digit meaning was task-relevant for comparisons between digits but not for the other comparisons. Consistent with this hypothesis, responses were significantly faster for digits than for letters in the "more/less" classification task, but no reliable advantage was observed for digits in the "same/different" classification task. Although the interaction between display type and stimulus duration did not quite reach significance, $F(1,41) = 3.503$, $MSE = 3738$, $p < .07$, planned comparisons revealed that the 52 ms advantage for digits in the "more/less" classification task was highly significant, $t(41) = -2.9$, $p < .007$, but the difference between response times for digits (756 ms) and letters (773 ms) in the "same/different" task was not significant, $t(41) = -1.16$, $p > .25$. Thus, although it appears that responses were somewhat (though not reliably) faster for digits than for letters even in the physical comparison task, it is clear that responses to the same digits were much faster than responses to letters when the meaning of the digits could be used to facilitate performance in the task. Accuracy was high across all conditions and mirrored the pattern observed in response times, with the fastest condition (digit classification in the "same/different" task) yielding the highest accuracy (92.8%) and the slowest condition (letter classification in the "more/less" task) yielding the lowest accuracy (86.6%). Thus, the digits advantage observed in response times cannot be attributed to a speed/accuracy trade-off. There was a slightly greater accuracy advantage for digits in the "more/less" task than in the "same/different" task (a difference of 1.7%), leading to a marginally significant stimulus type × task interaction, $F(1,41) = 3.86$, $MSE = 0.0346$, $p < .06$. This advantage must be interpreted with caution, however, as the greater accuracy for digit comparisons than for letter comparisons was significant in both the "more/less" task (3.72%; $t = 4.56$, $p < .0001$) and the "same/different" task (2.02%; $t = 2.76$, $p < .01$).

Table 3
Experiment 3 ($n = 42$): mean reaction time (ms) and accuracy (parentheses) for each stimulus type and task

Task	Stimulus type	
	Digits	Letters
"Same/different" judgment	755 (.93)	773 (.91)
"More/less" judgment	815 (.90)	867 (.87)

4.3. Discussion

When numeric meaning was task relevant (more/less task), performance was significantly better for digit displays as compared to letter displays. However, when numeric meaning was not relevant to the task (same/different task), performance for digit displays was similar to performance for letter displays. Therefore, the results of Experiment 3 confirm that the numeric meaning of digits only facilitates performance when it is task relevant.

5. Experiment 4

In Experiment 4, participants were allowed to view the displays of digits, letters, and shapes for as long as they wished. If there is a process specialized for the rapid extraction of meaningful information, then it should be more likely to be used when the visual information is available only for a short period of time. Given more time, such "gist-based" comparisons should give way to more accurate processes such as counting the individual items in the displays. If this is the case, then the reaction time and accuracy advantage found for digit comparisons in Experiments 1 and 2 with brief stimulus durations should be eliminated in Experiment 4 with unlimited stimulus duration. Furthermore, if participants in Experiment 4 are counting individual items in the displays and then comparing the displays, reaction times should be longer and accuracy should be higher for all comparisons in Experiment 4 than for comparisons in the previous experiments.

5.1. Method

5.1.1. Participants

Nine University of British Columbia undergraduates participated in Experiment 4 and received partial course credit in a department psychology course or monetary compensation ($5) in exchange for their voluntary participation. All had normal or corrected-to-normal vision.

5.1.2. Design

The design of Experiment 4 was identical to that of Experiment 1 except in one respect. Participants in Experiment 4 again compared digit displays based on the larger average value and compared letter and shape displays based on the greater occurrence of a target. However, rather than manipulating stimulus duration, the stimulus display remained on the screen until a response was made. Participants were instructed to respond as quickly and accurately as possible.

5.2. Results

Table 4 lists the mean reaction times and accuracy across the four display types in Experiment 4. There was no longer an advantage for processing digit displays at unlimited stimulus durations. Performance was similar in the digits, letters, and sideways letters conditions. However, because response times were much slower for sideways digits than for the other three display types, there was a significant main effect of display type, $F(3,24) = 4.76$, $MSE = 758{,}511$, $p < .02$. This main effect was eliminated when the sideways digits condition was excluded from the analysis, $F(2,16) = 1.28$, $MSE = 615{,}207$, $p > .30$. Accuracy did not differ across display types, $F < 1$. Furthermore, participants' responses to digit displays in Experiments 1 and 2 were faster than in Experiment 4, $t(16) = -5.171$, $p < .001$ (E1) and $t(19) = -5.91$, $p < .001$ (E2), however, accuracy was very similar across the three experiments in this condition.

Table 4
Experiment 4 ($n = 9$): mean reaction time (ms) and accuracy (parentheses) for each display type

Stimulus duration	Digits	Sideways digits	Letters	Sideways letters
Unlimited	2019 (.86)	3489 (.86)	2603 (.84)	2477 (.83)

5.3. Discussion

The results of Experiment 4 revealed that comparisons between digit displays were made with similar speed and accuracy as comparisons between the other display types. This suggests that numeric information was no longer rapidly utilized to facilitate comparisons when participants were not under time constraints that might make it more practical to base comparisons on a rough estimate of the numeric meaning of the scene than on the identity of individual items. Responses in Experiment 4 were much slower than in Experiments 1 and 2, but accuracy was quite similar across the three experiments. This demonstrates that although participants who were shown the displays for an unlimited duration took longer to compare the displays, they did so no more accurately than participants who were shown the displays only briefly. Interestingly, this finding also suggests that participants incorrectly believed that counting individual items would lead to better performance than relying on the output of the rapid process used in Experiments 1 and 2; although they spent a long time counting items in the displays, this did not improve accuracy in the task when the instructions stressed both speed and accuracy.

Another interesting finding of Experiment 4 was that participants took longer to compare displays of sideways digits than to compare any of the other display types, but they compared all display types with similar accuracy. This suggests that processing was somehow inhibited when processing sideways digits displays. A possible post-hoc explanation of these results is that participants had enough time to recognize that the items were sideways digits and thus attempted to process them as such in order to improve performance, but in doing so, actually took more time than it would have taken to compare the items as shapes. Further support for this proposal comes from direct observation.

When viewing sideways digit displays during the practice portion of Experiment 4, most participants began to tilt their heads to the side. When questioned, these participants reported that they were attempting to obtain a better view of the sideways displays. Despite this subjective impression, there was no advantage for upright digits relative to letters and sideways letters in Experiment 4, and in fact, performance was actually impaired by attempts to process sideways digits as upright digits. These participants were immediately told to maintain upright head position for the duration of the experiment.

The faster reaction times for digit displays in Experiment 1 (in which viewing time was manipulated) vs. reaction times for digits in Experiment 4 (in which viewing time was unlimited) suggested that when there were no limits on the amount of time spent viewing each display, participants no longer used a rapid process to compare the digit displays. Instead, as indicated by the similar mean reaction times across display types in Experiment 4, digits were now processed in a similar manner as letters and shapes.

6. Experiment 5

Subjects may use the rapid extraction of numeric meaning as a processing shortcut, saving time when quickly evaluating multielement visual displays. However, it is unclear whether this shortcut is also able to save processing resources. Although the attentional requirements of the rapid extraction process have been investigated from the perspective of spatial attention (Chong & Treisman, 2005a), the central attentional requirements of this process have not yet been explored (Johnston, McCann, & Remington, 1995). Chong and Treisman's work suggests that the process operates for all items in parallel across a display, preattentively without requiring spatial attention. However, the work of Johnston et al. (1995) suggests that input attention can be distinguished from central attention. As such, it is possible that the process might not be able to be carried out in parallel with the resource-demanding stages of a second task. However, the results of previous investigations of interference of digit meaning on task performance (Dehaene & Akhavein, 1995; Henik & Tzelgov, 1982; Windes, 1968) suggest that numeric information is extracted from digits automatically, even when it is detrimental to the task at hand. This suggests that the extraction of numeric meaning might be accomplished without requiring limited processing resources (Kahneman, 1973). Furthermore, work on the rapid extraction process and spatial attention was carried out for the extraction of statistical descriptors. Therefore, the attentional requirements of extracting numeric meaning might be different. In order to investigate the processing resource requirements of the rapid extraction of numeric meaning, Experiment 5 investigated whether this process could be executed in parallel with a second, resource-demanding process.

If this rapid extraction process requires central attentional resources that are also needed for a second demanding process, it will suffer when carried out in parallel with the second process. The central attentional resource requirements of the rapid extraction process can be investigated using the psychological refractory period (PRP) paradigm (e.g., Pashler, 1994). In PRP experiments, two stimuli are presented at varying stimulus-onset asynchronies (SOAs) and each requires a speeded response. Typically, response times in Task 2 increase as SOA decreases, suggesting that some resource needed to complete Task 2 has been allocated to Task 1 and is largely (or completely) unavailable for carrying out Task 2 (e.g., Tombu & Jolicœur, 2003). Although Task 2 is waiting for resources to be allocated so that its resource-demanding stages can be carried out, stages that precede these bottleneck stages can be carried out in parallel with Task 1. If these early stages of Task 2 finish before the bottleneck stage of Task 1 is complete, a period of waiting results, in which no further work is done in Task 2. This period of waiting is sometimes called "cognitive slack." Work in Task 2 resumes when the capacity-limited stages in Task 1 have been completed and the limited resource can be allocated to Task 2. Because there is a period of waiting in early Task 2 processing, the duration of an early stage of processing in Task 2 can be increased experimentally without increasing Task 2 reaction time (see Fig. 5). In other words, the effect of increasing the difficulty of an early stage of Task 2 is absorbed into cognitive slack (McCann & Johnston, 1992; Pashler & Johnston, 1989; Van Selst & Jolicœur, 1997; see Tombu & Jolicœur, 2003, for a different model leading to the same prediction). As a result, the PRP paradigm can be used as a diagnostic tool to localize the effect of a manipulated factor: underadditive interactions with SOA suggest that the factor affected a stage of processing before the bottleneck stage, whereas additive effects with SOA suggest that the factor affected a stage in or after the bottleneck stage. In Experiment 5, if the rapid extraction of numeric meaning requires central attentional resources, then we should find an additive effect of this process with SOA. However, if the process does not require central resources, then the effect should be absorbed into "cognitive slack," and decrease with decreasing SOA, producing an underadditive interaction.

6.1. Methods

6.1.1. Participants

Fifty-five undergraduate and graduate students, and two post-doctoral fellows volunteered their participation in exchange for pay or partial course credit. All participants reported normal or corrected-to-normal vision. Of these 57 participants, three were rejected based on poor performance in Task 1 (less than 70% accuracy) and nine more were rejected based on poor performance in Task 2 (less than 60% accuracy in any condition). The analyses reported below were based on data from the remaining 45 participants.

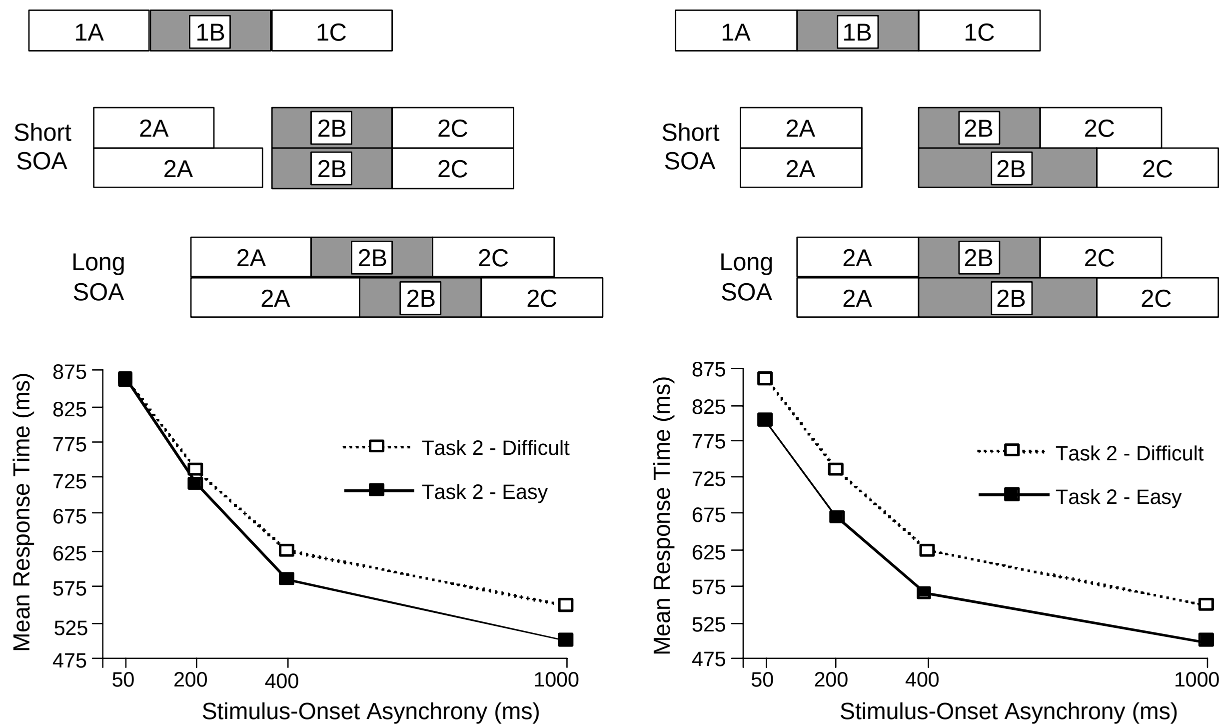

Fig. 5. Top: the length of each box in the diagram corresponds to the duration of a stage of processing in each task. Stages that cannot be carried out in parallel with each other appear in grey. The top-most set of stages on the left and right halves of the diagram correspond to Task 1 processing. The left half of the top of the diagram depicts the effect of a factor manipulation on an early stage of Task 2 processing at a short SOA (middle set of boxes) and a longer SOA (bottom set of boxes). The right half of the top of the diagram depicts the effect of a factor manipulation on a central stage of Task 2 processing at a short SOA (middle set of boxes) and a longer SOA (bottom set of boxes). Bottom: graphical depictions of the predictions made by the bottleneck model for Task 2 response times, for a manipulation affecting an early stage (left) and a manipulation affecting a central stage (right). See text for details.

6.1.2. Stimuli

Stimuli were displayed on CRT color monitors by 386, 486, or Pentium class personal computers. Stimuli were presented in white on a black background at high contrast. The stimulus for Task 1 was the letter "X" or "Y" drawn with straight line segments, presented at the center of the display. Each Task 1 stimulus subtended $0.6° \times 1°$ of visual angle. Task 2 stimuli were the same as the stimuli used in Experiment 3, with a single ring of characters presented on each trial rather than two side-by-side rings. Each ring was made up of digits, sideways digits, or letters. In order to minimize the trials per participant in Experiment 5, we did not include a sideways letters condition, because the results of the previous experiments suggested that including the sideways digits condition was sufficient to examine processing based on shape and form similarities. When digits were presented, the ring of stimuli contained 2's and 5's. On half of these trials, four 2's and two 5's were shown. On the remaining trials, two 2's and four 5's were shown. Each location in the ring contained a 2 or 5 with equal probability across the entire experiment. When sideways digits or letters were presented, they were displayed in exactly the manner just described for digits.

6.1.3. Procedure

Each trial began with a single "X" or "Y" displayed at fixation for 250 ms. Participants were instructed to identify the letter as quickly and accurately as possible by pressing one of two keys on the computer keyboard with the middle and index fingers of the left hand. Participants pressed the "a" key if "X" was displayed and the "s" key if "Y" was displayed. The ring of stimuli for Task 2 was presented at one of three SOAs (80, 200, or 1000 ms) from the Task 1 stimulus. On those trials with an SOA of 80 ms, the stimuli for Tasks 1 and 2 were presented concurrently for 170 ms (i.e., the letter for Task 1 was presented alone for 80 ms, then together with the ring of stimuli for Task 2 for 170 ms, then cleared from the screen). Similarly, when the SOA was 200 ms, the stimuli for Tasks 1 and 2 were presented concurrently for 50 ms. The ring of stimuli for Task 2 was displayed until a response was made. Participants were instructed to determine which of the two stimuli occurred more frequently in the ring of stimuli, as quickly and accurately as possible. They were also told that they would be unable to make their response in Task 2 until the computer had registered a response in Task 1. On digits trials, participants were instructed to press the "<" key on the computer keyboard when there were more 2's than 5's present in the display. When there were more 5's, the ">" was to be pressed instead. On the sideways digits and letters trials, the "<" key was pressed to indicate a greater occurrence of sideways 2's or p's, and the ">" key was pressed to indicate a greater occurrence of sideways 5's or q's. A note was attached to the monitor to remind participants of the stimulus-response mapping. To encourage fast responding, a message instructing participants to respond more quickly was presented following the second of the participant's responses if the response time in Task 1 exceeded 900 ms or if the response time in Task 2 exceeded 1200 ms (if both criteria were exceeded, two messages were shown). After a response was made in Task 2, the display was cleared and replaced with two feedback symbols presented on either side of screen center. The symbol on the left provided feedback for Task 1 and the symbol on the right provided feedback for Task 2. A "+" was displayed to indicate a correct response and a "×" was displayed to indicate an incorrect response. Participants pressed the spacebar to clear away the feedback symbols and initiate the next trial. After a delay of 500 ms, the stimulus for Task 1 was displayed.

6.1.4. Design

Trials were constructed by factorially combining the three SOA conditions with the two stimuli for Task 1 (X or Y) and the two types of Task 2 displays that could appear on each trial (i.e., more 2's than 5's or more 5's than 2's, etc.). The experiment was divided into three counterbalanced phases according to the type of stimuli displayed for Task 2 (digits, sideways digits, or letters), with each participant completing all three phases. Each phase consisted of 19 blocks of 16 trials. The first four blocks of each phase were identified as practice and data from these trials were excluded from the analyses presented below. In total, participants completed 912 trials in a single one-hour session. Of these, 192 were treated as practice, leaving 720 trials for data analysis.

6.2. Results

Mean RTs for each SOA are displayed for Tasks 1 and 2 as a function of display type (digits, sideways digits, or letters) in Table 5. reaction time data from trials on which both responses were made correctly were first screened for outliers using a recursive elimination procedure, which computes criteria for excluding scores based on sample size (see Van Selst & Jolicœur, 1997, for details). This outlier analysis was applied separately to reaction times from Tasks 1 and 2, resulting in the exclusion of 3.0% of correct reaction times from Task 1 analyses and 2.3% of correct reaction times from Task 2 analyses. The mean reaction time in Task 2 was computed for each participant in each condition and submitted to a 3×3 repeated-measures ANOVA with the factors SOA (80, 200, or 1000 ms) and display type (digits, sideways digits, or letters). A second ANOVA was carried out with Task 1 reaction time as the dependent variable. Accuracy for the two tasks was analyzed with separate ANOVAs, with the same factors and levels as were used in the analysis of reaction times. Fig. 6 shows the reaction time in Task 1 and Task 2 for each SOA as a function of display type.

Table 5
Experiment 5 ($n = 45$): mean reaction time (ms) and accuracy (parentheses) for each SOA (ms) and display type listed by task

SOA	Digits	Sideways digits	Letters
Task 2			
80	985 (.71)	1074 (.67)	1063 (.69)
200	872 (.69)	990 (.71)	955 (.67)
1000	660 (.68)	748 (.66)	721 (.66)
Task 1			
80	565 (.96)	549 (.94)	574 (.96)
200	535 (.96)	530 (.95)	545 (.96)
1000	538 (.96)	546 (.95)	539 (.96)

6.2.1. Task 2

Task 2 reaction times increased with decreasing SOA, producing a significant main effect of SOA, $F(2,88) = 351$, $MSE = 11{,}067$, $p < .001$. Comparisons between digits (839 ms) were made more quickly than either comparisons between sideways digits (938 ms) or comparisons between letters (913 ms), but the main effect of display type was not quite significant, $F(2,88) = 2.95$, $MSE = 120{,}894$, $p < .06$. Planned comparisons revealed that comparisons between digits were faster than comparisons between the other two display types, $t(44) = 3.06$, $p < .004$, but comparisons between sideways digits and letters did not reliably differ, $t(44) = .48$, $p > .63$. The effect of display type did not vary as a function of SOA, as reflected by a nonsignificant SOA × display type interaction, $F(4,176) = 1.44$, $MSE = 3084$, $p > .22$. The additivity of the effect of this rapid extraction process and SOA is underscored by a second ANOVA on Task 2 reaction times, which collapsed the sideways digits and letters condition into a single condition and compared performance in this condition to performance in the digits condition as a function of SOA. In this analysis, the advantage of digits over the other two conditions was 96, 108, and 91 ms at the 80, 200, and 1000 ms SOAs, respectively, and there was again no interaction between SOA and display type, $F < 1$.

Task 2 accuracy did not differ reliably across the three conditions, ranging from 67% to 69%, $F < 1$. Although performance in this range might appear to be lower than expected, it should be remembered that participants were given a deadline of 1200 ms in which to make their Task 2 responses. This was done in order to discourage them from trying to count individual elements in the displays, which, as demonstrated by Experiment 4, eliminates the need for a process that rapidly extracts meaning from displays. There was a slight tendency for accuracy to be lower at the longest SOA than at the two shorter SOAs, but this effect was not significant, $F(2,88) = 2.06$, $MSE = 14.2$, $p > .13$. The interaction between display type and SOA was not significant, $F < 1$.

6.2.2. Task 1

Whereas Task 2 reaction times increased 331 ms as SOA was decreased from 1000 to 80 ms, Task 1 reaction times increased only 21 ms over this range. Nevertheless, this

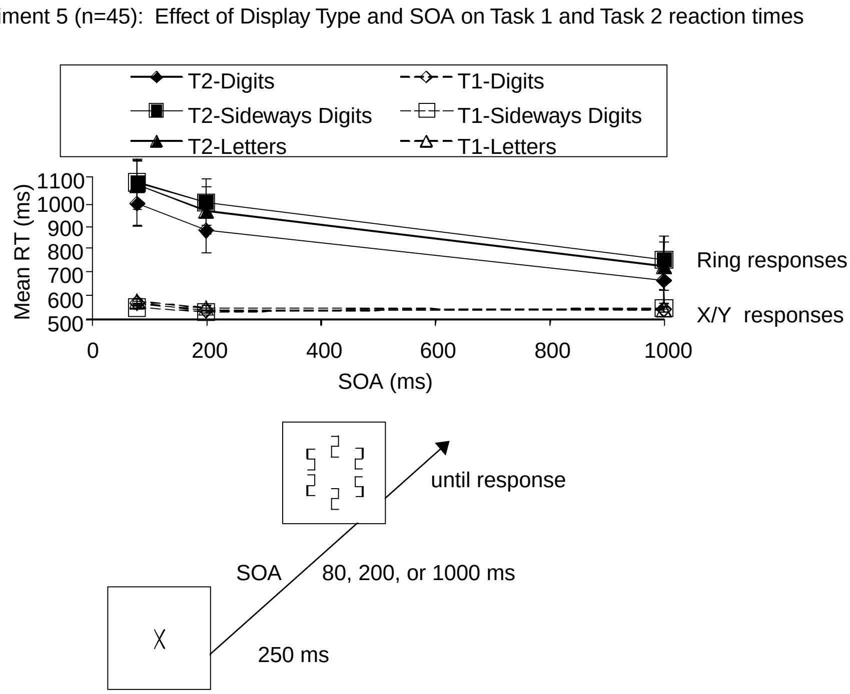

Fig. 6. Experiment 5 ($n = 45$): solid lines/symbols represent reaction times for the three display types in Task 2 and dashed lines/open symbols represent the corresponding reaction times in Task 1. The effect of display type was additive with SOA in Task 2 and there were no significant effects in Task 1. Error bars represent one standard error.

increase led to a significant main effect of SOA, $F(2,88) = 3.65$, $MSE = 7132$, $p < .04$. A significant interaction between SOA and display type was observed, $F(4,176) = 4.37$, $MSE = 766$, $p < .004$. However, this interaction seems to be the spurious result of a difference in the general pattern of reaction times as a function of SOA in the sideways digits condition relative to the other two conditions. Whereas the function relating reaction time and SOAs tended to be U-shaped in the digits and letters conditions, this same function had an inverted U-shape for the letters condition. Because the meaning of this interaction is unclear, it will not be discussed further. The main effect of display type was not significant in Task 1 reaction times, $F < 1$.

Task 1 accuracy ranged from 95% to 96% across the three display types. A slight tendency for accuracy to be worse for letters followed by sideways digits could be indicative of a trade-off between Task 1 and Task 2 in this condition and produced a marginally significant main effect of display type, $F(2,88) = 2.72$, $MSE = 2.21$, $p < .08$. Neither the main effect of SOA nor the interaction between SOA and display type was significant.

6.3. Discussion

The absence of an interaction between SOA and display type suggests that the rapid extraction of numeric information that leads to shorter response times for digits as compared to the other stimulus types was not carried out in parallel with response selection in Task 1. Put differently, the additive effects of display type and SOA indicate that numeric information was not rapidly extracted from the stimulus displays while central processing resources were allocated to response selection in Task 1. This finding suggests that the rapid extraction of numeric information requires central attention.

7. General discussion

Overall, this study provided evidence that numeric meaning can be rapidly extracted from digit displays. In Experiment 1, we found that digits were processed more quickly and accurately than familiar letters or simple shapes. Performance was similar for comparisons between sideways digits, letters, and sideways letters but slower and less accurate than for comparisons between digits, suggesting that differences in spatial structure alone could not explain the observed advantage for digit stimuli. Comparing the effect of rotation for digits and letters provided additional support for the claim that numeric meaning was responsible for the observed digits advantage. Rotating digits led to slower comparisons, but rotating letters had no effect. This suggests that the numeric meaning that facilitated comparisons between displays of digits was lost when the digits were rotated. Therefore, the main conclusion of Experiment 1 was that numeric information can be processed faster and more accurately than information about familiarity or shape.

Manipulating the exposure duration of the displays had no measurable effect on the speed or accuracy of comparisons. Because the advantage for digits was found even at the briefest stimulus durations (80 ms), the lack of an effect of exposure duration suggests that the process responsible for the digits advantage operates rapidly, before response interference or interferences occurring later in processing. Future work will be directed toward exploring whether the perceptual representation of the digits displays is influenced by the rapid extraction of numeric meaning from the displays, or whether this processing shortcut exerts its influence at a later stage.

In addition to stimulus properties such as luminance (Oliva & Torralba, 2001; Torralba & Oliva, 2003) and average size (Ariely, 2001; Ariely & Burbeck, 1995; Chong & Treisman, 2003), the present study demonstrated that numeric value of digit stimuli could also be rapidly extracted using a processing shortcut. This is an important finding because previous investigations have shown that physical stimulus properties can be rapidly extracted, but the present study shows that more abstract, higher-order stimulus properties are also extracted by such rapid processes.

A remaining question from Experiment 1 was whether the meaning of the stimuli was specified by the instructions given to participants. With digit displays, participants were instructed to base their comparisons on average value, whereas they were told to report the more frequent occurrence of a target shape when comparing other display types. This may have affected the approach that participants took to processing the digit displays, which may have led to the observed differences in performance across display types. If differences in task instructions led to faster comparisons between displays of digits, then equating the task instructions across conditions should eliminate the advantage. The results of Experiment 2 showed no effect of controlling for task instructions on digit processing. However, further research is needed to determine whether conceptual meaning can be specified by task instructions. For example, the conceptually ambiguous stimulus  might be processed differently if it were to be specified as a letter "s" instead of a digit "5" in future experiments (Jonides & Gleitman, 1972). One possibility is that the task could be changed to reveal an advantage for processing letters over digits. This could be accomplished by changing the nature of the comparison task to a more qualitative task in which letter identity is relevant to the task at hand, in contrast to the present quantitative task, which implicitly imparts task relevance to digit stimuli.

Experiment 3 was carried out to directly demonstrate the importance of task relevance in the rapid extraction of numeric meaning. When numeric meaning was task-relevant, performance was significantly better for digit displays as compared to letter displays. However, when numeric meaning was not relevant to the task, performance for digit displays was similar to performance for letter displays. Experiment 3 confirmed that the numeric meaning of digits was driving the digit advantage observed in Experiments 1 and 2 because numeric meaning could be used as a basis for comparisons between digit displays but no such basis of comparison existed for the other display types.

Experiment 4 showed that numeric information was not rapidly extracted when sufficient time was given to identify individual stimuli. In Experiment 4, participants were allowed to make comparisons without the time constraints of the brief presentations used in the previous experiments. Although participants were given unlimited time to compare displays, task instructions stressed accuracy and speed equally. The results of Experiment 4 revealed similar reaction times and accuracy for all stimulus types, with the exception of increased reaction times for sideways digits. These results suggested that the process responsible for the rapid extraction of numeric information acts to provide a quick summary of the visual display but is abandoned in favor of a slower counting process when stimuli can be processed to the level of identification. Interestingly, the results of Experiment 4 suggest that counting does not actually lead to more accurate performance, which implies that participants are uncertain of the reliability of the information output by the process that rapidly extracts meaning from visual displays. This can be interpreted within the context of recognition memory research, in which participants often mistake the fluency of processing a stimulus for prior experience with that stimulus (e.g., Jacoby, Kelley, & Dywan, 1989; Whittlesea, 1993). Perhaps in the present experiments, observers experienced a feeling of fluent processing when using the rapid extraction process (i.e., because the comparison is made quickly, it feels subjectively easy). Because they could not attribute this feeling of fluency to prior experience with the displays, participants might have discounted the feeling—and the accompanying solution generated by the rapid extraction process—as suspect (Collister & Tversky, 2000). Subjectively, using the rapid extraction process might have felt too much like guessing, leading to a preference for counting individual items when sufficient time was given to do so, even though accuracy was no better with counting (Experiment 4) than with using the rapid extraction process (Experiments 1 and 2).

It is interesting to note that although this processing shortcut is fast, it nevertheless requires attention. Experiment 5 showed that this process could not be carried out in parallel with a demanding process in a second task. This is surprising in light of the findings of Dehaene and Akhavein (1995), Henik and Tzelgov (1982), and Windes (1968) which showed that the meaning of digits is automatically extracted even when it is detrimental to the task at hand. One possible resolution to this conflict is that meaning may be automatically extracted from digits but making comparisons based on this information requires central attention (Oriet, Tombu, & Jolicœur, 2005). This raises the possibility that numeric information is extracted automatically but not able to be used without requiring attention.

8. Concluding remarks

Because our visual representations must always keep pace with our ever-changing environments, the visual system may rely on rapid processes to form ''quick and dirty,'' ''just in time'' representations of our dynamic surroundings that act as an outline and hold together the illusion of visual perception (Rensink, 2000). This study demonstrated that the visual system is able to rapidly extract numeric information from brief displays of digits, just as it is able to extract statistical properties such as mean luminance and size. Further research is needed to determine whether other types of conceptual information can also be rapidly extracted from brief displays.

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