Published in final edited form as:

Neuropsychologia. 2008 August ; 46(10): 2532–2544. doi:10.1016/j.neuropsychologia.2008.04.003.

The Processing of Non-symbolic Numerical Magnitudes as Indexed by ERPs

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Abstract

Previous research has shown that, in the context of event-related potential (ERP) prime-target experiments, processing meaningful stimuli such as words, phonemes, numbers, pictures of objects, and faces elicit negativities around 400 milliseconds. However, there is little information on whether non-symbolic numerical magnitudes elicit this negative component. The present experiments recorded ERPs while adults made same/different judgments to serially presented prime-target pairs of non-symbolic numerical stimuli containing the same, close, or distant quantities. In Experiment 1, a negativity between 350–450 ms was elicited for targets preceded by primes of unequal quantity, and this was greater for close than for distant quantities. Change direction (decreasing or increasing) also modulated a similar negativity: a greater negativity was elicited by targets preceded by larger than by smaller quantities. Experiment 2 replicated the numerical distance and change direction effects for numerical judgments, but found no negative distance effect in a color comparison task when the same stimuli were used. Additionally, ERP effects of numerical distance were found under implicit conditions, and task proficiency in the number condition modulated implicit and explicit numerical distance ERP effects. These results suggest that the neural systems involved with processing numerical magnitudes contribute to the construction of meaningful, contextual representations, are partly automatic, and display marked individual differences.

Keywords

semantic; number; priming; N400; proficiency; individual differences; automatic

Previous research has shown that, in the context of an event-related potential (ERP) prime-target experiment, processing meaningful stimuli such as words (Kutas & Hillyard, 1980), phonemes (Coch, Grossi, Skendzel, & Neville, 2005; Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001), numbers (Niedeggen & Rösler, 1999), pictures of objects (McPherson and Holcomb, 1999), and faces (Müntz et al, 1998) elicit negativities around 400 milliseconds (N400). These negativities have been shown to be modulated by relatedness and repetition, where target stimuli that are unrelated to primes elicit larger negativities than related targets, and non-repeated target stimuli elicit larger negativities than repeated stimuli. However, numerical magnitudes can be represented symbolically (e.g. *three*, 3) and non-symbolically (e.g. dots on a die), raising the question as to whether or not non-symbolic magnitudes will elicit negativities around 400 ms.

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ERP studies of semantic priming find modulations of the N400 by the semantic relatedness of prime and target stimuli. Originally identified in a sentence reading paradigm to semantically incongruous words (Kutas & Hillyard, 1980), the N400 in lexical priming increases in amplitude with an increase of semantic distance between prime and target words. When prime and target words are identical, processing of the target word is facilitated and the N400 is attenuated (Misra & Holcomb, 2003). In addition to word stimuli, N400 effects have been found in response to discriminating facial expressions and identities (Münter et al, 1998), phonological comparisons of rhyming and non-rhyming targets (Coch, Grossi, Skendzel, & Neville, 2005; Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001), and pictures of semantically related versus unrelated real objects (McPherson & Holcomb, 1999). McPherson and Holcomb (1999) suggest that this negativity and negativities around 400 ms more generally reflect the process of attending to the prime-target relationship, where “larger N400s are associated with more effortful integration.” Although it is accepted that these negative effects do not necessarily share the same topography, what they do have in common is that they are all elicited by stimuli considered to be contextually meaningful (see Kutas & Federmeier, 2000, for a good discussion).

Like words, the domain of number is meaningful and is characterized by the so-called distance and magnitude effects. Early investigations into the psychophysics of number processing led to the discovery that the numerical distance between two Arabic numerals is negatively correlated with response times (RT) of comparative judgments (Moyer & Landauer, 1967). This distance effect has been replicated using different forms of quantity representation and appears to be an invariant feature of processing numerical magnitude: subjects are quicker to respond to large differences than they are small ones (Barth, Kanwisher, & Spelke, 2003; Pinel, Dehaene, Riviere, & LeBihan, 2001; Pinel, Piazza, Le Bihan, & Dehaene, 2004). Moreover, distinguishing numerosities seems to follow Weber’s law of psychophysics, which states that recognizing a magnitude difference depends more upon the ratio of the two quantities being compared than the absolute difference between them (Brannon, 2005; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 2000; Whalen & Gallistel, 1999).

Negative ERP effects have also been found using symbolic numerical stimuli (Niedeggen & Rösler, 1999). Negativities in the 360–440 ms time window were greater in response to incorrect solutions compared to correct ones, demonstrating something similar perhaps to a form of identity priming. Similar to the semantic N400, this arithmetic negativity was reduced by the relatedness of the target to the primes: ERP negativities were attenuated in response to related errors that were close or medium in numerical distance compared to related errors that were far. Using number word stimuli, Kaan (2005) also found relatively negative ERP effects between 300–500 ms to far compared to close numerical distances in a number comparison task. Analysis also revealed significant effects of change direction, whether a subsequent value was greater (increasing) or less (decreasing) than the antecedent value, such that decreasing trials were responded to with more errors and longer latencies than increasing trials, and elicited greater negativities in three epochs: 150–300 ms, 300–500 ms, and 500–700 ms.

Symbolic and non-symbolic number stimuli were used by Temple & Posner (1998) in an ERP study with children and adults making comparisons to a quantity of five. Stimuli consisted of Arabic numerals and dot arrays and were either numerically close (i.e. four and six) or numerically distant (i.e. one and nine). Both adults and children showed greater amplitudes of the first negative (N1) component for numerically close digits and dots than for numerically distant digits and dots, followed by a greater posterior positivity (P2p) for numerically distant than for close dots. Adults showed a reverse pattern in the P2p for digits, suggesting a possible confound with sensory processing differences in the stimuli leading to ERP differences (Libertus, Woldorff, & Brannon, 2007). Relevant to the current study, but not discussed by Temple & Posner (1998), the waveforms for adults (Temple & Posner, 1998, Fig. 3) show a

greater negativity to close than to far distances between approximately 300–600 ms in the dot condition.

In addition to differences in physical stimuli, comparing magnitudes around five is potentially confounded because of the likelihood of invoking more than one system capable of representing magnitude. Behavioral studies have demonstrated that Weber's law applies to the discrimination of a wide array of quantities, but debates persist on whether small quantities (usually one to four items) and larger quantities are represented by separate systems (Feigenson, Carey, & Hauser, 2002) or are instead represented along a single magnitude continuum (Cordes, Gelman, Gallistel, & Whalen, 2001). For example, Trick & Pylyshyn (1994) have raised the hypothesis that small quantities can be represented internally as individual object files, and that the system for representing object files is different from that used in the representation of larger quantities. Until the debate surrounding a distinct neural system for small quantities is resolved, intermixing small and large numerical magnitudes within a stimulus set entails tenuous assumptions.

Present Experiments

The present experiments sought to determine whether or not the comparison of non-symbolic numerical magnitudes in a prime-target task would elicit the effects typically found in prime-target studies to other stimuli that are meaningful. We predicted that targets of quantities that differ from primes would elicit greater negativities around 400 ms than repeated quantities. In agreement with the hypothesis that negativities around 400 ms reflect the effort of integration, we also predicted that quantities close in numerical distance would elicit greater negativities than quantities that are numerically distant.

To avoid problems with stimuli used in some of the previous studies, three primary constraints were implemented. The first constraint was to use only large quantities (> 10) in the dot arrays to avoid uncertainties regarding the possible differences in processing small and large set sizes. The second and third constraints were to control for item size in the prime stimuli and total luminance in the target stimuli (Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). Varying item size across prime stimuli discourages participants from using size rather than quantity to perform the discrimination tasks. Keeping total luminance constant across the target stimuli is important because Pinel and colleagues (2004) have found that differences in luminosity also display distance effects, confounding decisions of numerical distance.

Experiment 1

Methods

Participants—Fifteen right-handed participants (10 female) between the ages of 19 and 39 ($M = 26.8$) reporting normal or corrected-to-normal vision and with no known neurological impairments were recruited from the University of Oregon campus and surrounding community. All participants signed IRB-approved informed consent forms and were paid for their time.

Stimuli—Thirty-two prime and twenty target stimuli each containing a set size of 16, 20, 24, or 30 white dots against a black background were generated within a 12.29 cm circle. Total luminance in the target stimuli was fixed, and item size was varied across prime stimuli, as discussed by Piazza et al (2004). Target stimuli were paired with prime stimuli such that set size ratios between prime and target were 1:1, 2:3, 3:2, 4:5, or 5:4. Thus, each target stimulus appeared containing the same, a close, or a far number of dots with respect to the prime. Every pair of stimuli in the ratio of 1:1 was presented twice so that 50% of the trials (320 trials) compared stimuli of the same set size, and 50% compared stimuli of a different set size. Of the

pairs that were different, 50% (160 trials) were close in number (ratios 4:5 and 5:4) and 50% (160 trials) were far (ratios 2:3 and 3:2).

Although a major aim of this study was to assess the effects of numerical distance, a second method of grouping trial types was also possible and reveals the effects of change direction: trials that show a relative increase (ratios 2:3 and 4:5) or a decrease in quantity (ratios 3:2 and 5:4) are grouped together. Given a target's set size and distance from the prime, change direction can be determined. For example, a *close* trial with a target of set size 24 will also be a *decrease* trial because the prime is determinately of set size 30, while a *far* trial with a target set size of 24 will have a prime of 16 and therefore be an *increase* trial. Thus, one way of exploring a Set Size by Distance interaction is to examine a main effect of Change Direction.

Procedure—Participants sat comfortably in a dimly lit, electrically shielded acoustic chamber, between 60–65” away from a CRT monitor which presented stimuli within 6° of visual angle. Trials were initiated by the participant and began with a 1000 ms display of a green fixation cross on a black background. The fixation remained on screen throughout the entire trial. After the initial fixation, the prime stimulus was displayed for 500 ms, followed by a 500 ms inter-stimulus interval and a 500 ms display of the target stimulus. Trials ended with a 700 ms fixation display during which participants could still respond. Participants were instructed to pay attention to the quantity of dots presented in the first display and to respond as quickly, but as accurately, as possible as to whether the second display contained the same or a different number of dots before the fixation disappeared from the screen. Participants were also instructed to ignore dot size and were informed that it was variable and uninformative for the task. Trial types were presented pseudorandomly such that no more than three trials of one ratio or target set size were presented in a row. Every participant received the same order of trials. A practice block using similarly constructed dot stimuli was given to participants with verbal feedback on the accuracy of each response from the experimenter until the task and response buttons were learned. Trial initiations and responses were made using two (vertically oriented) buttons (top for “same” and bottom for “different”) of a standard video game controller with either the left or right index finger. Response hand was counterbalanced across participants. To reduce movement related artifacts, participants were encouraged to keep their eyes focused on the fixation and to refrain from blinking while the fixation was displayed.

ERP Acquisition—The electroencephalogram (EEG) was recorded from 29 tin electrodes attached to an elastic cap (Electro-Cap International, Eaton, OH). Ten sites were situated within the International 10–20 system and the remaining 19 were arranged among these to form a grid focused over the posterior region of the head, as described and depicted by Coch, Skendzel, Grossi, & Neville (2005). Additional electrodes were placed at the outer canthi of right and left eyes and just beneath the right eye to record electrooculograms and to monitor eye movement. Consistent with previous work coming out of our lab, scalp electrodes were referenced to the right mastoid electrode during recording and re-referenced off-line to the average of the right and left mastoid. Impedances were kept below 3K Ω for scalp electrodes, 2K Ω for mastoid electrodes, and 5K Ω for eye electrodes. The EEG was amplified (10k times) with Grass 7P511 amplifiers (filtered .01 to 100Hz bandpass, 60Hz notch) and digitized at a sampling rate of 250Hz using Labview software.

Data Analysis

Behavioral data: Accuracy and response latency were collected for all trials. For the *same* condition, only data from one-half of the repeated trials randomly sampled from across the entire experiment were used in the analyses. Trials that did not generate responses within the 1200 ms time-window were counted as incorrect and excluded from response time (RT) analyses. Two participants were excluded for failing to respond correctly within the allotted

time window in more than 50% of the total trials. Repeated measures ANOVAs (RM-ANOVA) using Set Size (16, 20, 24, 30) and Distance (Same, Far, Close) were first conducted with accuracy and RT measures. Subsequently, a RM-ANOVA with Change Direction (Same, Increase, Decrease) as a factor was conducted to examine a Set Size by Distance interaction with accuracy scores and RTs. Significant main effects were followed up with paired-sample t-test pair-wise comparisons.

ERP Data: ERP averages were generated for each participant for Same, Close, and Far distance targets relative to the prime, as well as for targets having an Increase and Decrease in quantity, using a 100 ms pre-stimulus baseline. Data presented in the figures were low-pass filtered at ~15 Hz, while raw data used for analysis was processed using a 60 Hz notch filter. Participant's data were visually inspected for artifacts to identify individually set parameters to be used in a standard artifact rejection routine to eliminate trials contaminated by eye and movement artifacts. Because early (< 350 ms) visually evoked potentials differ morphologically over anterior and posterior sites, and these effects were most clearly observed over midline sites, peak measurements for these early components were taken from anterior site Fz and posterior site INz, while later negative peak measurements (> 300 ms) used for analysis were taken from the averages from each of the 24 channels listed below.

Mean amplitude measurements were taken between 350–450 ms and between 450–600 ms time-windows. The effects of Distance and Change Direction were analyzed separately for each of these time-windows. Twenty-four channels (F7/8, F3/4, T3/4, C3/4, CT5/6, CP1/2, T5/6, P3/4, TO1/2, PO1/2, IN3/4, O1/2) were included in the analysis with the following electrode-location factors: Hemisphere (Hemi; left, right), Lateral-medial (Lat-Med; two levels), and Anterior-posterior (AP; frontal, central, central-parietal, parietal, parietal-occipital, occipital). Repeated-measures ANOVAs with Greenhouse-Geisser correction for non-sphericity were used. Significant main effects were followed up with pair-wise comparisons using RM-ANOVA and the electrode-location factors. Tests of statistical significance for behavioral and ERP data of Experiment 1 are reported in Table 2.

Results

Behavioral—The behavioral results show that participants responded most slowly and least accurately to trials for Close, most quickly and accurately for Far, while accuracy and RT measures for Same were in between those of Far and Close (Table 1). Main effects of Distance (Table 2) were found for accuracy ($p < 0.001$) and RT ($p < 0.05$), as were significant Set Size $\times$ Distance interactions: accuracy ($p < 0.001$); RT ($p < 0.001$). Follow up analyses showed that participants were more accurate for Far than for Same and Close. Participants were marginally more accurate Same than for Close.

As a result of the set size constraints placed upon the stimulus set, the distance of each set size determines whether dots are added to or subtracted from a display. Because of this, the Set Size $\times$ Distance interactions were explored with a Change Direction factor. The analysis of accuracy measures using Change Direction returned a nearly significant effect ($p = 0.05$). Trials having an increase in quantity were responded to with greater accuracy than trials in which the change was a decrease in quantity. Analyzing RT by Change Direction was also significant ($p < 0.01$). Paired-sample t-tests showed that Far and Increase generated faster responses than did Close and Decrease, respectively.

ERP Data—As shown in Figure 1, ERPs to Same, Far, and Close elicited a series negative and positive components that varied in amplitude and latency as a function of electrode location. Over anterior sites, negative peaks occurred at 100 and 230 ms, positive peaks at 170 and 280 ms. Over posterior sites, positive peaks at 100 and 230 ms were separated by a negative

peak at 156 ms. ERPs to all three conditions show a negative deflection that began around 300 ms and peaked between 350–450 ms: Same (360 ms), Far (365 ms), and Close (444 ms). Analysis of these early components using local peak amplitude measurements returned only a significant effect of Distance at Fz for the N2 component ($p < 0.05$). Follow up t-tests showed that Same was more negative than Close ($p < 0.05$) and Far ($p < 0.05$). Subsequent to these negative peaks appeared a broad positivity peaking around 600 ms.

The amplitude of the negativity between 350–450 ms was larger for “different” trials than for Same trials, greater for Close than for Far (Table 1). A significant main effect of Distance ($p < 0.05$) led to follow up analyses showing that Close was significantly more negative than Same ($p < 0.05$) and Far ($p < 0.01$). No interactions were found between Distance and electrode location factors.

The mean amplitudes between 450–600 ms for Distance showed a different pattern from the amplitudes between 350–450 ms, such that Far was the least negative, followed by Same, while amplitude for Close remained the most negative. A RM-ANOVA on these means also returned a main effect of Distance ($p < 0.05$) and no interactions with electrode location factors. Pairwise comparisons show that the Far condition was significantly less negative than Close ($p < 0.01$) but only marginally less negative than Same.

ERP data were also averaged into Increase and Decrease conditions. Although 50% of the stimuli of Increase and Decrease trials were non-identical, luminance across all target stimuli was constant. The ERP waveforms for Change Direction (Fig. 2) appeared very similar to the numerical Distance waveforms, with a larger negativity for Decreasing than for Increasing. Local peak latencies were patterned similarly to the Distance waveforms: Increasing (369 ms), Decreasing (428 ms). Submitting the means from between 350–450 ms to a RM-ANOVA revealed a significant main effect of Change Direction ($p < 0.05$). Follow up comparisons found significant differences between Decrease and Same, and Decrease and Increase. No interactions were found between Change Direction and electrode location factors. The mean amplitude measures for Change Direction between 450–600 ms were not significantly different from each other as a main effect ($p > 0.8$) or in any interaction with electrode location factors.

Discussion

The results from the analysis of behavioral measures are consistent with previous reports of distance effects using non-symbolic numerical stimuli (Barth, Kanwisher, & Spelke, 2003). Namely, participants were less accurate with and took longer to respond to close distances than to far distances. Accuracy and RT measures for Same were found to be in between those of Close and Far. For both accuracy and RT measures, Set Size $\times$ Distance interactions led to the analysis of behavioral data using a Change Direction factor, which found that participants were less accurate with and took longer to respond to a decrease in quantity than to an increase in quantity, consistent with previous behavioral results on change direction (Kaan, 2005). Accuracy and RT measures for Same trials were in between those of Increase and Decrease. As predicted, the ERP waveforms in the 350–450 ms time window displayed a pattern of mean amplitudes that can be described as a relative negativity for change trials, greater for the Close condition than for the Far condition. A similar pattern was found for Change Direction, such that the Decrease condition elicited a greater negativity than the Increase condition, which were also consistent with Kann (2005) using number word stimuli.

Although the ERP averages for the Close condition were most negative between 350–450 ms and 450–600 ms, the relative amplitudes for the Far and Same conditions were different between these time windows. Accuracy and positive ERP amplitudes between 450–600 ms were in order from greatest to least, Far, Same, and Close. The effects from this later time-window are consistent with an overlap between the negative components and an ensuing P300

for each of the Distance conditions. In discrimination tasks, P300 amplitude is found to be negatively correlated while P300 latency is positively correlated with difficulty (Picton, 1992). This means that the P300 would overlap with and diminish most the negative effects of the Far condition, and affect least the negativity in the Close condition. Because these later effects are not likely to be of particular relevance to the processing of non-symbolic numerical magnitudes, their significance is not emphasized.

The present data support the hypothesis that negativities around 400 ms reflect an effort of integration. The behavioral data show that the Close condition and the Decrease condition generated the lowest accuracies and longest response times, making it reasonable to assert that the Close and Decrease conditions required the most effort. These two conditions also generated the greatest negativities in the ERP waveforms between 350–450 ms.

However, it is possible that these ERP data simply reflect a strategy or cognitive process particular to the task, bearing only a coincidental relation to number processing. That is to say, these ERP effects could be driven primarily by the difficulty of task and less by the nature of the stimuli. If this were the case, then processing numerical quantity could be substituted with the processing of another parametrically manipulated dimension with similar results. A second experiment was therefore designed to replicate the findings from Experiment 1 and to test the hypothesis that the negativity found in the 350–450 ms time-window is an index of the effort involved with processing numerical magnitude per se rather than an index of a domain-general task-related process.

Several constraints were identified for the design of Experiment 2 in addition to those imposed upon Experiment 1. The first was that the experimental design should abide by “the Hillyard Principle” (Luck, 2005): using physically identical stimuli while changing only the task. To afford the deployment of separate tasks with the same stimuli, each stimulus should have two orthogonal dimensions to ensure that any observed ERP effects are due solely to the task. Second, the difficulty of the second task should be titratable along a single dimension to provide a stimulus set with comparable error rates across the levels of both dimensions. Prior research has shown that compared to color stimuli, number stimuli lead to greater activation of the IPS regions thought to be responsible for processing numerical magnitude information (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003). Thus, implementing a color distance task, manipulating hue, appeared to be the most feasible way to meet all of these criteria.

Dot stimuli were developed with colored backgrounds to allow same/different judgments to be performed on either number or color dimensions. Using the same stimuli in an orthogonal task also affords the ability to analyze ERP data as a function of implicit processing of the unattended dimension. Previous reports of N400 modulation under masked conditions (Kiefer, 2002; Misra & Holcomb, 2003) suggest that these negative ERP effects of non-symbolic numerical magnitude processing might also be elicited implicitly. If processing numerical information is obligatory, then we should see evidence of modulated ERP activity during both explicit and implicit magnitude processing.

In the first experiment it was noticed that some of the participants whose judgment accuracy was low did not exhibit as much differentiation between ERP waveforms for Distance as participants whose accuracy was high. Thus an additional hypothesis tested in Experiment 2 was that proficiency in the number task would distinguish ERP results for the number task; specifically, that higher performers would be more likely to show the same trend for distance effects found in Experiment 1.

Experiment 2

Methods

Participants—Twenty-three right-handed participants (14 female) between the ages of 19 and 31 ($M = 22.9$) reporting normal or corrected-to-normal vision and with no known neurological impairments were recruited from the University of Oregon campus and surrounding community. All participants signed IRB-approved informed consent forms and were paid for their time.

Stimuli—Dot stimuli were generated using a modified version of the Matlab programs used to generate the stimuli for Experiment 1. The background color within a 12.29 cm diameter circle, against which white dot stimuli were set, varied among four shades of green (Table 3) selected after pilot testing for a color discrimination task such that the pattern of accuracy results for hue distance would closely match the pattern of accuracy results obtained in Experiment 1. Introducing background colors brought performance in the number discrimination task for close distances (4:5 and 5:4 ratios) to chance levels, so ratios were changed to 1:1, 7:12, 12:7, 2:3, and 3:2 using the quantities 14, 21, 24, and 36. The four shades of green were counterbalanced for quantity of dots and dot size across the prime stimuli, and for quantity of dots across the target stimuli. This allowed each target stimulus to appear as a Same, Close, and Far Distance, in both Color and Number tasks. Background and fixation colors were set to grey.

Procedure—The tasks and timing for Number and Color tasks of Experiment 2 were the same as for Experiment 1, except the duration of the response window extended to 1500 ms by displaying the fixation for an additional 300 milliseconds at the end of each trial. Some of the pilot participants explained that they had used a strategy of categorizing the number of dots into small, medium, and greater quantities. To prevent participants from using different strategies for each task, potentially based on inaccurate information (e.g. thinking there were only three stimulus types), participants were informed that they would see four set sizes of number of dots, or four shades of green, depending on which task they would be subsequently performing. Participants were also informed of the probabilities of obtaining a Same, Close, or Far trial. In the color task, participants were instructed to respond indicating whether or not there had been a change in color of the background and to ignore the dots. In the number task, the instructions were to respond indicating whether or not there had been a change in the quantity of dots and to ignore dot size and the colored background. Color and Number tasks were performed in separate blocks, prior to which participants underwent an automated practice block requiring a correct response within the 1500 ms response window to 7 of the previous 10 practice trials. Response hand and order of task were counterbalanced across participants.

Data Analysis

Behavioral Data: A RM-ANOVA using Task (Number, Color) and Distance (Same, Far, Close) for accuracy and RT measures was conducted first to examine the main effect of condition. Accuracy and RT data for each condition were then analyzed separately, using the Distance and Change Direction factors used in Experiment 1 for the Number condition, and Distance as a factor for the Color condition.

ERP Data: Mean ERP amplitudes were measured for the same 24 channels analyzed in Experiment 1 between 350–450 ms for Color and Number tasks, and between 450–600 ms for the Number task only. Additionally, mean ERP amplitudes were measured for the Number task between 450–700 ms to assess a late positive effect in the different proficiency groups (see below). Two participants were excluded from the ERP analysis for having fewer than 15% usable trials after artifact rejection. A RM-ANOVA including two levels of Task (Number,

Color), three levels of Distance (Same, Far, Close), and the electrode location factors as in Experiment 1 was first run to assess a main effect of Task. Subsequently, Color Distance and electrode location factors were included to analyze ERP data from the Color task, while Number Distance and Change Direction factors were run with electrode location factors in separate RM-ANOVAs for the Number task. Interactions with electrode location factors were further explored with step-down analyses, and significant main effects were explored with pairwise comparisons. Means and results of tests for statistical significance are reported in Table 4 and Table 5.

Event-related potentials to target stimuli for the implicit Number and Color tasks were averaged from stimuli presented during the explicit Color and Number tasks, respectively. Trials with prime-target pairs that were not presented in the explicit condition were excluded for a possible total of 96 trials for each level of Distance before artifact rejection. Because implicit Number Distance effects occurred within a later time window, mean ERP amplitudes for the implicit analyses were measured between 450–525 ms. Statistics for implicit ERP effects are reported in Table 4 and Table 6.

Proficiency: To test the hypothesis that numerical proficiency modulated ERP effects for non-symbolic number processing, participants were divided into Higher Proficiency for Number (HPN) and Lower Proficiency for Number (LPN) groups based on their numerical magnitude judgment accuracy. Of the 21 participants with useable ERP data, 10 (7 female) who scored less than 50% accuracy in at least one trial type (e.g. set size: 36; distance: Same) of the Number task formed the LPN group. Of the remaining 11 participants, the participant with the lowest total average score was excluded, leaving 10 participants (6 female) in the HPN group as well. Fortunately, exactly one-half of each group had received either the Color or Number task first, controlling for the order of presentation. A similar method was used to divide the 21 participants into Higher Proficiency (HPC) and Lower Proficiency (LPC) groups for the Color task in order to more directly compare the effects of Proficiency between Number and Color tasks. Eleven participants scored less than 50% accuracy in at least one trial type in the Color task. The participant with the highest average accuracy of these 11 was removed from the analysis, leaving 10 participants in each HPC and LPC group. Of the HPC group, six had received the Number task first, and for the LPC group, four had received the Number task first.

RM-ANOVAs with Proficiency as a between-subjects factor were used to analyze the behavioral measures of the Higher and Lower proficiency participants for each of the Number and Color tasks. Significant effects were followed up with RM-ANOVAs and paired samples or independent samples t-tests. Electrode location and either Number Distance or Change Direction as within-subject factors, and Proficiency as a between-subjects factor, were used in mixed design ANOVAs for each Number-related ERP measurement. Significant interactions for all ERP analyses were further explored with step-down analyses.

Results

Behavioral

Color vs. Number: Omnibus ANOVAs on the RT and accuracy measures (Table 4) show that participants were both faster ($p < 0.01$) and more accurate ($p < 0.05$) at color than quantity discrimination. Main effects of Number Distance were obtained for both accuracy ($p < 0.001$) and RT ($p < 0.01$), replicating the results of Experiment 1: Number Far trials were responded to most quickly and accurately, followed by Number Same and Number Close (Table 4 & Table 5). Similar to Experiment 1, Change Direction was significant for RT ($p < 0.001$) and approached significance for accuracy ($p < 0.06$), with patterns replicating those of Experiment 1. The behavioral data for Color Distance parallel those of Number Distance with significant

main effects for Color accuracy ($p < 0.001$) and RT ($p < 0.001$): Color Far trials were responded to most quickly and accurately, followed by Color Same and Color Close.

Higher vs. Lower Proficiency: Accuracy and RT analyses for the 20 HPN and LPN participants in the Number task show that the LPN group had significantly longer RTs and was less accurate than the HPN (Table 4 & Table 5). A significant Number Distance $\times$ Proficiency interaction was found for accuracy measures, $F(2,36) = 3.43$, ($p < 0.05$). Independent samples t-tests comparing the groups at each level of Number Distance show that the proficiency groups differed in accuracy for Number Close, $t(18) = 4.82$, $p < 0.001$, and Number Far, $t(18) = 3.53$, $p < 0.01$, but not for Number Same ($p > 0.62$). Comparing RT for HPN and LPN groups at each level of Distance found that the LPN group took longer to respond to Number Far, $t(18) = 2.52$, $p < 0.05$, and Number Close, $t(18) = 2.39$, $p < 0.05$.

Within groups, significant effects of Distance in accuracy were found for both HPN ($p < 0.001$) and LPN ($p < 0.05$), while only the HPN group had significant effects of Number Distance on RT ($p < 0.001$). No interactions were found between Number Direction and Proficiency ($p > 0.11$).

In contrast to the effects of Proficiency in the Number task, the HPC group obtained significantly greater accuracy than the LPC group (Table 4 & Table 5), but longer RTs, indicating the presence of a speed-accuracy trade off. Significant interactions between Color Distance and Proficiency for accuracy measures, $F(2,36) = 13.73$, $p < 0.001$, led to pairwise comparisons for accuracy, which revealed that HPC and LPC groups differed in accuracy for Color Close, $t(18) = 3.88$, $p < 0.01$, but not Color Far or Same (both $p > 0.23$). There was no interaction between Color Distance and Proficiency for RT ($p > 0.83$).

ERP Data – Explicit Processing

Color vs. Number: As seen in Figure 3, the ERPs in the Number and Color tasks displayed similar oscillations during the first 250 ms, which did not differ in local peak amplitude measurements by either Task or Distance ($p > 0.05$). While ERPs in the Color task demonstrated a positive peak at around 400 ms, ERPs in the Number task showed a positive peak around 300 ms followed by a negative component with peaks ranging from 363–402 milliseconds. Analysis of local peak amplitude for the N2 component in the Number task at site Fz was not significant ($p > 0.42$).

Visual inspection of the average waveforms for Color Distance and Number Distance (Fig. 3) clearly show that ERP effects for color and number processing are different within the 350–450 ms time window. A main effect of Task ($p < 0.05$) and a Task $\times$ Distance interaction, $F(2,40) = 26.78$, $p < 0.001$ confirm different ERP effects of Distance for Number and Color. A main effect of Number Distance ($p < 0.05$) was obtained, with ERP means similar to those in Experiment 1: Number Far and Number Close were more negative than Number Same, greater for Number Close than for Number Far, and local peak latencies occurred between 350–410 ms: Same (402 ms), Far (363 ms), and Close (368 ms). A Number Distance $\times$ Lat-Med interaction, $F(2,40) = 5.63$, $p < 0.05$, showed that Distance effects were strongest over medial sites.

A main effect of Distance was also found for Color ($p < 0.001$), but in contrast to the Number task, Color Far generated a large positivity, while Color Same and Color Close were less positive. Interactions between Color Distance $\times$ Lat-Med, $F(2,40) = 14.24$, $p < 0.001$, and Color Distance $\times$ AP, $F(10,200) = 9.82$, $p < 0.001$, showed that Color Distance effects were strongest more laterally and over parietal and occipito-parietal sites.

The pattern of ERP results for Change Direction was also similar to Experiment 1 (Fig. 4). Local peak latencies were similar for Increase (373 ms) and Decrease (379 ms) conditions. A main effect of Change Direction was found, with significant differences between Same and Decrease, and between Increase and Decrease. Interactions of Change Direction $\times$ Lat-Med, $F(2,40) = 4.96, p < 0.05$, and Direction $\times$ AP, $F(10,200) = 5.29, p < 0.01$, showed that effects of Change Direction were most prominent over medial posterior-parietal sites.

Results from the analysis of mean ERP amplitudes between 450–600 ms for the Number task yielded a marginal effect of Distance, $F(2,40) = 3.0, p = 0.067$. An interaction between Distance, Laterality, and Caudality was also found, $F(10,200) = 2.76, p < 0.05$. Further analysis of this interaction returned a main effect of Distance for this later time window over Lateral sites only, $F(2,40) = 3.82, p < 0.05$. The means for this effect were consistent with a certainty based P300 explanation, Far being responded to with the most certainty (6.1 μV), followed by Same (5.6 μV) and Close (5.5 μV).

Higher vs. Lower Proficiency: The ERPs for Number Distance were markedly different for the HPN and LPN groups. The HPN group ERPs demonstrated a clear Number Distance effect (Fig. 5), while the LPN group did not show virtually any differentiation between 350–450 ms for Number Distance. Proficiency interacted with Distance and Lat-Med ($p < 0.05$), leading to separate RM-ANOVAs for the HPN and LPN groups. The HPN group had a marginal main effect of Number Distance ($p = 0.051$), and a significant Distance $\times$ Lat-Med interaction ($p < 0.05$). Separate analyses over medial and lateral sites for the HPN group returned a significant main effect of Number Distance over medial sites ($p < 0.05$) and an effect approaching significance over lateral sites ($p < 0.09$).

Analysis of the LPN group ERPs for Number Distance did not lead to any significant effects. In contrast to Number Distance, no significant effects or interactions involving Proficiency as a factor were obtained for Change Direction.

Color distance ERPs for HPC and LPC groups showed similar patterns, but with a more focal and larger amplitude positivity for the HPC compared to the LPC group (Fig. 6). A RM-ANOVA returned a Proficiency $\times$ Color Distance $\times$ Laterality interaction, $F(2,36) = 6.91, p < 0.05$. Analysis of ERP data for the proficiency groups separately returned significant main effects of Color Distance for both HPC, $F(2,18) = 24.65, p < 0.001$, and LPC, $F(2,18) = 16.00, p < 0.001$. Pairwise comparisons for HPC and LPC groups showed that both obtained significant differences between Color Far and Color Same, and Color Far and Color Close (all $p < 0.001$), neither group had differences between Color Close and Color Same (both $p > 0.13$). These results show that while Proficiency modulated the size of the Color Distance effects, the pattern of Color Distance effects were more or less similar between groups.

The Number task ERP waveforms show that the late positivity for the LPN group extends beyond 600 ms (Fig. 5), therefore a mixed effects analysis was re-run using mean ERP amplitudes taken from between 450–700 ms. This analysis again returned a significant Proficiency $\times$ Distance $\times$ Laterality interaction, $F(2,36) = 5.11, p < 0.05$. Analysis by Proficiency group show that the LPN group obtained a main effect of Distance for the late positivity, ($p < 0.05$), but the HPN group did not ($p > 0.35$). Pairwise comparisons for the LPN group show that Far (6.7 μV) was significantly more positive than Same (5.7 μV), $F(1,9) = 8.96, p < 0.05$, but not more than Close (6.2 μV ; $p > 0.13$). Thus, while the Lower Proficiency group did not demonstrate the earlier negativity exhibited in the Higher Proficiency group data, they did show a later positivity consistent with the correlation between the P300 component and response latencies.

ERP Data – Implicit Processing

Color vs. Number: The ERPs for the implicit Number Distance (Fig. 7) and Change Direction conditions for all 21 participants show repetition effects similar to those found in the explicit Number Distance and Change Direction conditions, but smaller in amplitude differences and during a later time-window: Same (415 ms), Far (445 ms), Close (499 ms); Increase (419 ms), Decrease (466 ms). RM-ANOVAs returned interactions with Lat-Med for Number Distance ($p < 0.01$) and Change Direction ($p < 0.05$), but follow up analyses did not return an effect of Distance over lateral or medial sites, and the effects of Change Direction on mean ERPs over lateral sites only were inconsistent with those found in the explicit Change Direction condition. Likewise, the ERPs for the implicit Color Distance condition for all 21 participants did not show the Color Distance effects found in the explicit Color task ($p > 0.63$).

Higher vs. Lower Proficiency: Implicit Number Distance ERPs for the HPN group showed the Number Distance effects found in Experiment 1, while the ERPs for the LPN group demonstrated a relative negativity to Number Far (Fig. 5). Mixed effects ANOVAs with Proficiency as a factor (Table 6) returned a significant Proficiency $\times$ Number Distance $\times$ AP interaction ($p < 0.01$) and a Proficiency $\times$ Number Distance $\times$ Lat-Med $\times$ AP interaction ($p < 0.05$). Implicit Change Direction did not interact with Proficiency in any interaction with electrode location factors ($p > 0.06$).

Analysis of implicit Number Distance for the HPN group returned significant interactions with Hemi ($p < 0.05$) and Lat-Med $\times$ AP ($p < 0.05$). Over left hemisphere sites, a main effect of Number Distance was found, ($p < 0.05$), while over right hemisphere sites a Number Distance $\times$ Lat-Med interaction was found ($p < 0.001$). Analyzing HPN ERP amplitudes by AP row over lateral and medial sites separately returned no main effects ($p > 0.12$). However, orthogonal contrasts showed linear trends of Distance (Same - Far - Close) to be strongest medially over Central-Parietal ($p = 0.05$) and Parietal ($p = 0.06$) sites. In sum, ERP effects of implicit Number Distance were found to be left lateralized, but extended to right medial electrode locations, with a trend for these effects to occur over Central-Parietal and Parietal sites.

Analysis of implicit Number Distance for the LPN group lead only to a marginal main effect of Number Distance over Occipital sites ($p = 0.062$). However, this effect was not the same as that found in Experiment 1. Rather, ERP amplitudes were more negative for Number Far than for Number Same and Number Close (Table 4).

The average ERP waveforms for implicit Color Distance by HPC and LPC (Fig. 6) show that while neither group exhibited patterns similar to explicit Color Distance, the LPC group showed a pattern of activity similar to the Number Distance effects. Including Proficiency as a factor for implicit Color Distance returned only marginal interactions between Proficiency and Color Distance by Hemi ($p < 0.07$) and by Lat-Med ($p < 0.07$), but to guard against making a Type II error, implicit Color Distance effects for HPC and LPC groups were analyzed separately. Interestingly, the LPC group obtained a nearly significant main effect of implicit Color Distance, $F(2,18) = 3.36, p < 0.07$, while the HPC group did not obtain a significant main effect or interaction (all $p > 0.27$). Given that the LPC group showed a similar albeit less focal Color Distance effect compared to the HPC group, it unlikely, though still possible, that the LPC implicit Color Distance effect is reflecting a more efficient color comparison process. Rather, it could be that the LPC group fared poorly on the Color task because they were less able to filter the irrelevant numerical information in the display, suggesting that this group would have been similarly affected by color changes in the Number task.

Discussion

The present data suggest that the ERP effects for number found in Experiment 1 and Experiment 2 are indexing magnitude processing. Although Color trials were responded to more accurately and quickly than Number trials, the effect of Distance on RT and accuracy measures for Color and Number paralleled one another. This suggests that if the ERP effects found in the 350–450 ms time window were strictly related only to difficulty, then the patterns of ERP activity for Number Distance and Color Distance should be similar. However, this was not the case. Rather, Color Far elicited a large positivity compared to Color Close and Color Same, while ERP data for Number showed that Number “different” conditions elicited the most negative waves, greater for Number Close and Decrease than for Number Far and Increase respectively. The consistency of these effects between experiments supports the idea that these ERP effects are an index of processing non-symbolic numerical magnitude and are not simply a result of task demands or difficulty.

On the other hand, both Color and Number tasks elicited a positive component, albeit at different latencies, that is deserving of some attention. The amplitude of the positivity elicited by the Color task was found to be large and early, while the positivity found in the Number task occurred later. This latency difference is consistent with the positive correlation between P300 latency and difficulty, as suggested by the overall higher accuracy and faster response times in the Color compared to the Number task. This explanation is further corroborated by the explicit Color Distance data when broken down into HPC and LPC groups. The HPC group showed a prominent and early peak compared to the LPC group, which demonstrated a reduced positivity for Color Far. However, accuracy and RTs were not significantly different between Color Same and Color Far, but the ERP amplitudes were, leaving some room for doubt in attributing the positivity elicited by Color Far to certainty.

Another explanation comes from Szucs, Soltész, Czigler, & Csépe (2007), who have shown with a matching task that number and letter categorical mismatches do elicit an N400 but that color mismatches do not. Although an attempt was made to control for the adoption of different strategies between color and number tasks by informing participants of the four set sizes, four colors, and the probabilities of receiving each trial type they would be receiving, we cannot rule out the possibility that different strategies were used. For example, comparisons of set size may have been carried out upon categorized stimuli, while comparisons of color were not, or vice versa. If different strategies were adopted, they were adopted without instruction, suggesting that each task lends itself to a different strategy. Whether or not the implementation of different strategies explain the differences in ERPs for color and number, each type of information is likely to recruit different neural processing mechanisms.

A surprising finding was an effect of Change Direction on behavioral and ERP measures. Research on numerical magnitude processing has found considerable consistency in the idea that numerical discriminability follows Weber’s law and is ratio dependent (Brannon, 2005; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 2000; Whalen & Gallistel, 1999). With at least one exception (Kaan, 2005), much of the number literature has focused on ratio dependency with little direct exploration of Change Direction effects, so there is relatively little research to appeal to. However, one thought is that non-symbolic magnitudes are neurally represented by summation coding as opposed to place coding (Meck & Church, 1983; Roggeman, Verguts, & Fias, 2007; Verguts & Fias, 2004). In this case, detecting an increase in numerical magnitude would involve neural activity from populations that were more or less silent, while detecting a decrease would be hindered by the residual activity of representing the larger number, and in part be constrained by the refractory period assigned to those populations. Because the current study was not designed to directly address this question, the effects of Change Direction found here only suggest future directions for research.

Number proficiency was also found to be a significant factor, such that the HPN group, which was more accurate and responded more quickly in Number trials, displayed the Number Distance ERP effects found in Experiment 1. The LPN group, on the other hand, obtained significant effects of Number Distance in accuracy measures, which was driven mainly by the higher accuracy for Far compared to Same and Close distances, but also in the later positive ERP component occurring between 450–700 ms. Interestingly, the HPN group did not show an effect of Number Distance for this latter time window. These results suggest that while the HPN group engaged a relatively fast and automatic process in detecting numerical differences, the LPN group engaged a slower, more effortful, and less efficient ensemble of resources, showing also that different levels of discriminability can be reflected in ERP data. One question this raises is that with slightly larger distance ratios, might we observe the ERP effects of distance in the LPN individuals similar to the distance effects we see in HPN individuals with small distance ratios? A related question is whether discriminability can be improved with practice, and if an improvement will be reflected in a changed neural organization. Change Direction as a factor was not found to interact with Proficiency, suggesting that HPN and LPN participants were similarly influenced by whether a change in quantity was increasing or decreasing.

Implicit ERP effects were found for Number Distance, but not for Change Direction. These data suggest that the human nervous system is continuously extracting information concerning numerical magnitude from the environment, given differences in discriminability. It is interesting to note that the pattern of implicit Number Distance effects for the LPN group showed a relative negativity to Number Far targets, indicating that the LPN group may have been processing Number Close as Number Same, an idea that is consistent with the behavioral data for this group. A question is then raised as to why this group showed Number effects in the implicit condition but not in the explicit condition. One strong possibility is that in the explicit condition, the amount of controlled effort obscured the effects of automatic processing. Holcomb (1988) found that encouraging participants to use strategic resources in analyzing prime-target semantic relationships elicited larger amplitude N400s than when the prime-target relationships were processed automatically, without strategy. It is possible that the overt processing of numeric stimuli by the LPN group increased the amplitude gain enough in all number distance conditions to wash out a numerical distance effect completely, while in the absence of such strategic processing a number distance effect remained observable. That is to say, all number comparisons were difficult for the LPN group, leading to an enhanced N400 for all numerical distances. In addition, trials in the implicit condition were not selected according to accuracy, e.g. 40% of Close trials were excluded from explicit Number ERP averages for the LPN group, while every trial was potentially included in the implicit condition averages. The inclusion of these data may partly explain the difference between ERP averages of explicit and implicit number conditions for the Lower Proficiency group.

The finding of a significant effect of Color Distance in the implicit condition is unclear, and there are at least two good reasons to doubt its validity. First, unlike the implicit Number Distance effects, it was the LPC group that showed ERP effects in the implicit condition, not the HPC group. It seems reasonable to expect the more capable of two groups at detecting differences explicitly to engage the stimuli implicitly. Second, the implicit Color effects for this group did not match their explicit Color effects. A more plausible explanation is that this weak effect is a false positive. For the LPC group, a change in background color may have made the number task more difficult, leading to increased negativities for the trials in which color change took place and giving the appearance of an implicit Color Distance effect.

Assuming the implicit effects are not valid, the question of why Color Distance and Change Direction effects don't occur implicitly is still unanswered. It's possible that the neural systems important in processing small color differences of the type employed here are not automatic;

that keeping abreast of minute changes in hue is not something the human brain has evolved to do inattentively. Another explanation contrasts foreground with background. A study by Turatto, Angrilli, Mazza, Umiltà, & Driver (2002) has shown that while changes in the foreground of a visual display modulate ERPs with or without attention, changes occurring in the background modulate ERPs only with attention. The findings of Turatto et al (2002) were found here as well; changes taking place in the foreground (number) yielded implicit ERP effects while background changes (color) did not. In the implicit Change Direction condition, Proficiency was not found to be a significant factor, but it was close. It may be the case that there is an interaction between Change Direction and Number Distance that cannot be resolved using the paradigm employed here, and that dismissing an implicit Change Direction effect is premature.

Conclusion—Non-symbolic numerical magnitudes elicited ERPs during a prime-target task that were negative between 350–450 ms, similar to the N400s reported to other types of meaningful stimuli. These effects were dissociated from task difficulty by implementing an identical task with similar behavioral properties on an orthogonal dimension of the same stimuli, showing that number but not color stimuli elicit negativities between 350–450 ms. Second, an effect of Change Direction was found here that suggests a future avenue of research, and a potential amendment to the ratio dependency of processing non-symbolic numerical magnitudes. Third, proficiency differences in the behavioral measures corresponded to differences in the pattern of ERP response to making quantity comparisons. Finally, ERP effects of implicit processing of quantity between 450–525 ms were also modulated by these differences between higher and lower proficiency groups. These proficiency differences also suggest future directions of research aimed at identifying the developmental and plasticity profiles of the numerical magnitude system.

Acknowledgements

This research was supported by NIH, NIDCD, R01 DC00128 to H.N. Special thanks to Yoshiko Yamada and Ed Vogel for their thoughtful conversations, INSERM UNIT 562 for making stimuli generating syntax available, to members of the Brain Development Lab for help with pilot testing, and to the anonymous reviewers for their helpful comments.

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Figure 1.
ERP averaged waveforms to the target stimuli as a function of numerical distance from the prime.

Figure 2. ERP averaged waveforms to target stimuli as a function of either numerical distance or change direction.

Figure 3.

ERP averaged waveforms to target stimuli in the color task as a function of distance in hue, and in the number task as a function of numerical distance.

Figure 4.

ERP averaged waveforms to target stimuli in the number task as a function of change direction from the prime.

Figure 5.

ERP averaged waveforms to target stimuli for the Higher and Lower Proficiency groups in the Number task as a function of numerical distance from the prime.

Figure 6.

ERP averaged waveforms to target stimuli for the Higher and Lower Proficiency groups in the Color task as a function of color distance from the prime.

Figure 7.

ERP averaged waveforms to target stimuli under implicit conditions, at Left Hemisphere Medial site CP1. Figures 6a and 6b show the averages for all 21 participants for implicit Color (a) and implicit Number (b) distances. Figures 6c and 6d compare implicit Number Distances for Higher Proficiency (c) and Lower Proficiency (d) groups.

Table 1
Experiment 1 Behavioral (Accuracy and RT) and ERP Means

Source	Same	Far	Close	Increase	Decrease
Accuracy	0.65	0.82	0.51	0.74	0.59
RT (ms)	860	834	883	828	889
ERP 350–450 ms (μ V)	6.28	6.03	5.16	6.10	5.14
ERP 450–600 ms (μ V)	6.86	7.80	5.84	7.21	7.02

Table 2
Experiment 1 Behavioral (Accuracy and RT) and ERP Statistics

Source	(df)	Accuracy F or t	p <	RT F or t	p <	ERP N2 ^a F or t	p <	ERP 350–450 ms F or t	p <	ERP 450–600 ms F or t	p <
Distance	(2,24)	17.70***	0.001	5.31*	0.05	3.82*	0.05	4.87*	0.05	5.66*	0.05
Far vs. Same	(12)	3.38**	0.01	1.31	0.22	2.42*	0.05	0.35	0.57	3.03	0.11
Far vs. Close	(12)	8.73***	0.001	5.79***	0.001	0.05	0.96	12.14**	0.01	14.46**	0.01
Close vs. Same	(1,12)	2.14	0.054	1.56	0.15	2.63*	0.05	6.75*	0.05	2.26	0.16
Set Size × Distance	(6,72)	11.74***	0.001	17.51***	0.001	-	-	-	-	-	-
Change Direction	(2,24)	3.41	0.06	6.77*	0.01	1.66	0.21	4.57*	0.05	0.09	0.92
Increase vs. Same	(12)	1.41	0.19	1.72	0.12	-	-	0.23	0.64	-	-
Increase vs. Decrease	(1,12)	2.90*	0.05	4.79***	0.001	-	-	8.45*	0.05	-	-
Decrease vs. Same	(1,12)	1.07	0.31	1.63	0.14	-	-	5.27*	0.05	-	-

Note: t-test *df* and results appear in italics.

^aERP N2 statistics performed on channel Fz using local peak amplitude between 170–280 ms.

* *p* < .05.

** *p* < .01.

*** *p* < .001.

Table 3

HSB Values for Stimuli Colors

Color	H	S	B	Intensity (cd/m ²)
Green 1	67	100	39	10.8
Green 2	76	100	40	11.1
Green 3	83	100	41	10.9
Green 4	93	100	42	11.4
Grey	0	0	31	7.3
White	0	0	100	94.0

Note: H = hue. S = saturation. B = brightness.

Table 4
Experiment 2 Behavioral (Accuracy and RT) and ERP (Explicit and Implicit) means

Source	Task	Same	Far	Close	Increase	Decrease	
Accuracy	Color	0.91	0.94	0.67	-	-	
		0.89	0.95	0.77	-	-	
	Number	HPC	0.93	0.92	0.57	-	-
LPC		0.78	0.85	0.69	0.82	0.72	
RT (ms)	HPN	0.80	0.92	0.79	0.89	0.82	
		LPN	0.77	0.76	0.60	0.74	0.63
	Color	793	792	862	-	-	
		857	859	928	-	-	
		HPC	731	725	794	-	-
		LPC	891	854	896	838	911
Number	HPN	826	777	825	780	823	
	LPN	955	934	969	903	1000	
	Color	6.60	9.26	6.85	-	-	
Number		6.80	6.48	6.11	6.67	5.82	
		HPN (Medial)	8.83	7.84	7.23	-	-
Implicit ERP (μV) ^b	LPN	6.30	6.39	6.21	-	-	
		6.70	6.85	6.64	-	-	
	Color	7.27	6.89	6.85	7.27	6.59	
		Number	7.64	7.03	6.68	-	-
	HPN (Left Hemisphere)	6.70	5.56	6.45	-	-	
		LPN (Occipital)					

Note: Reported ERP means are from all 24 electrode sites unless otherwise indicated, in which case means are from sites producing a main effect Color and Number averages are from $n = 21$ participants.
HPN = Higher Proficiency Number ($n = 10$). LP = Lower Proficiency Number ($n = 10$).

^aMeasured from 350–450 ms.
^bMeasured from 450–525 ms.

Table 5
Experiment 2 Behavioral (Accuracy and RT) and Explicit ERP Statistics

Source	(df)	Accuracy		RT		All participants (n = 21)		450–600 ms	
		F or <i>t</i>	<i>p</i> <	F or <i>t</i>	<i>p</i> <	F or <i>t</i>	<i>p</i> <	F or <i>t</i>	<i>p</i> <
Color vs. Number	(1,20)	14.68**	0.01	8.01*	0.05	6.95*	0.05	-	-
Number Distance	(2,40)	11.15***	0.001	8.40**	0.01	3.45*	0.05	3.0	0.07
Far vs. Same	(20)	1.82	0.09	2.85*	0.05	1.51	0.24	2.39	0.14
Far vs. Close	(20)	9.69***	0.001	6.07***	0.001	2.95	0.11	8.33**	0.01
Close vs. Same	(20)	2.16**	0.05	0.41	0.70	5.17*	0.05	0.46	0.51
Color Distance	(2,40)	52.86***	0.001	17.90***	0.001	37.89***	0.001	-	-
Far vs. Same	(20)	1.97	0.07	0.08	0.94	37.81***	0.001	-	-
Far vs. Close	(20)	9.23***	0.001	7.94***	0.001	82.87***	0.001	-	-
Close vs. Same	(20)	6.43***	0.001	4.08***	0.001	0.69	0.42	-	-
Change Direction	(2,40)	3.11	0.06	11.85***	0.001	8.27**	0.01	-	-
Increase vs. Same	(20)	0.84	0.42	3.56**	0.01	0.22	0.65	-	-
Increase vs. Decrease	(20)	2.73*	0.05	4.35***	0.001	15.41**	0.01	-	-
Decrease vs. Same	(20)	1.51	0.15	1.30	0.18	11.65**	0.01	-	-
Proficiency participants (n = 10, n = 10)									
Number Task Proficiency	(1,18) ^a (2,36) ^b	Accuracy 14.94 ^a	0.01	RT 5.17 ^a	0.05	350–450 ms 2.35 ^b	0.12	450–700 ms 2.34 ^b	0.12
× Distance × Lateral-Medial	(2,18)	26.67***	0.001	14.21***	0.001	3.79*	0.05	5.11*	0.05
HPN Number Distance						4.49*	0.051	1.11	0.35
× Lateral-Medial						6.16*	0.05	-	-
@ Medial						5.05*	0.05	-	-
LPN Number Distance	(2,18)	5.03*	0.05	1.46	0.27	0.15	0.78	5.54*	0.05
Color Task Proficiency	(1,18) ^a (2,36) ^b	5.92 ^a	0.05	7.24 ^a	0.05	2.92 ^b	0.9	-	-
× Distance × Lateral-Medial						4.03*	0.05	-	-
HPC Color Distance	(2,18)	59.29***	.001	8.62**	0.01	24.65***	0.001	-	-
LPC Color Distance	(2,18)	22.83	.001	6.00	0.05	16.00	0.001	-	-

Notes: HPN = Higher Proficiency Number. LPN = Lower Proficiency Number.

^aBetween-subjects effects.

^bProficiency × Distance interaction. *t*-test *df* and results appear in italics.

*
p < .05.

**
p < .01.

p < .001

Table 6
Experiment 2 Implicit ERP Statistics

Source	(df)	F	<i>p</i> <
All participants (n = 21)			
Color Distance	(2,40)	0.42	0.64
Number Distance × Lat-Med	(2,40)	5.84**	0.01
@ Lateral	(2,40)	0.94	0.40
@ Medial	(2,40)	2.27	0.13
Change Direction × Lat-Med	(2,40)	3.80*	0.05
@ Lateral	(2,40)	3.70* ^a	0.05
@ Medial	(2,40)	2.14	0.14
Proficiency participants (n = 10, n = 10)			
Proficiency × Number Distance × AP	(10,180)	5.01**	0.01
Proficiency × Number Distance × Lat-Med × AP	(10,180)	2.78*	0.05
HPN Distance × Hemi	(2,18)	4.76*	0.05
HPN Distance × Lat-Med × AP	(10,90)	2.93*	0.05
@ Left Hemi	(2,18)	4.75*	0.05
@ Right Hemi ^b	(2,18)	17.52***	0.001
LPN Distance × AP	(10,90)	4.95*	0.05
@ Occipital	(2,18)	3.39 ^a	0.06

Note: AP = Anterior-Posterior. Lat-Med = Lateral-Medial. Hemi = Hemisphere. HPN = Higher Proficiency Number. LPN = Lower Proficiency Number.

^a Inconsistent with explicit condition data.

^b Number Distance × Lat-Med interaction.

* *p* < .05.

** *p* < .01.

*** *p* < .001