Symbolic Integration, Not Symbolic Estrangement, For Double-Digit Numbers

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Abstract

Symbolic and non-symbolic number representations are thought to share common neural substrates. However, recent studies have shown that the two numerical systems are more distinct than previously thought. These disparate findings may be explained by the use of sequential presentations of symbolic and non-symbolic quantities, the use of magnitude-reliant tasks, or the use of limited number ranges. We investigated whether adults integrate symbolic and non-symbolic numerical information during a non-magnitude-based task in which symbolic and non-symbolic double-digit numerical information is shown simultaneously. Participants viewed images in which symbolic numerals or letter pairs were superimposed on non-symbolic numerical stimuli and were asked to determine whether the text was a numeral or letter, ignoring the dots. After perceptual biases were taken into account, participants were more accurate and faster in their judgments when symbolic and non-symbolic information matched than when information mismatched, suggesting that adults can integrate symbolic and non-symbolic numerical information.

Keywords: number processing; symbolic integration; symbolic estrangement; symbolic numerical system; non-symbolic numerical system

Introduction

Educated humans have access to two types of numerical representations: exact, i.e., symbolic, number representations and approximate, i.e., non-symbolic, magnitude representations. These magnitude representations are thought to be at the core of the approximate number system (ANS), which imprecisely represents numerical quantities such that quantities at close ratios (e.g., '12' and '18') are harder to discriminate than quantities at distant ratios (e.g., '12' and '30') (Dehaene, 1992; Nieder & Dehaene, 2009). For educated human adults, symbolic and non-symbolic representational systems appear to overlap to a high degree, such that seeing a numeric symbol will activate a representation of its associated magnitude. For example, fMRI studies have found overlapping regions of activation when people view symbolic and non-symbolic numerical stimuli (e.g., Dehaene, Dehaene-Lambertz, & Cohen, 1998; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003) and when people perform mental addition on symbolic and non-symbolic stimuli (Venkatraman, Ansari, & Chee, 2005). Habituation paradigms also provide support for overlap. When the same numeric quantity is presented multiple times, the hemodynamic response associated with that quantity is diminished, even when the presentation format shifts between symbolic and non-symbolic notations (e.g., Kallai, Schunn, & Fiez, 2012; Piazza, et al., 2004). This suggests that the same neurons are activated when processing symbolic and non-symbolic numerical stimuli. Critically, higher levels of this "symbolic integration" are thought to support mathematical problem solving and math achievement (Geary, 2013; Holloway & Ansari, 2009).

However, recent behavioral and neuroimaging evidence questions the commonalities between symbolic and non-symbolic number representations. Symbolic numbers do not always automatically and effortlessly activate non-symbolic magnitudes (e.g., Lyons, Ansari, & Beilock, 2012; Wong & Szucs, 2013). With regard to math achievement, it has been found that both symbolic and non-symbolic representations serve as resources for mathematical problem solving, but that their contributions are unique, and the contribution of non-symbolic representations weakens after six years of age (Fazio, Bailey, Thompson, & Siegler, 2014). This suggests that "symbolic estrangement" may be occurring, in which mathematics depends primarily upon relations between symbolic numerals, with little meaningful support from ANS representations (Lyons, Ansari, & Beilock, 2012).

The differing perspectives on symbolic integration and symbolic estrangement may reflect issues of measurement. Most prior measures of symbolic integration are indirect: participants experience sequences of stimuli (i.e., a symbolic numerical stimulus followed by a non-symbolic one, or vice versa). Symbolic integration is thought to reflect experience in representing co-occurring and corresponding symbolic and non-symbolic stimuli, which is not well measured by these sequential procedures. In addition, the majority of prior studies require participants to make magnitude-based judgments (e.g., number comparison judgments). Such tasks could potentially prime the activation of one type of representation over the other, depending on the particulars of the task. Furthermore, prior research suggests that the type of magnitude judgments can influence the extent to which symbolic integration is found (Lyons & Beilock, 2013). Previous studies have also primarily investigated single-digit numbers or double-digit numbers of low quantity. It is possible that sampling more heavily across the full double-digit number range would also yield different integration results. The current study seeks to address these issues by using a novel experimental paradigm to assess symbolic integration.

We wanted to test whether adults would show evidence of symbolic integration when they are simultaneously presented with multi-digit symbolic and non-symbolic numerical information (see Figure 1). Instead of asking participants to make magnitude judgments, they completed a numerical version of the lexical decision task (henceforth known as the “Numberness task”), in which they judged whether text on a stimulus showed a numeral or letter pair. The stimuli also included non-symbolic number information in the form of a dot cloud, which either matched or mismatched the symbolic information in quantity. Because the task did not require magnitude processing, participants were not primed to process the stimuli through the ANS. This provided a cleaner measure of whether participants naturally integrated the two types of numerical formats. The paradigm’s design was inspired by prior research on integration effects in reading, in which speech sounds are presented with matching or mismatching Arabic letters (e.g., Blau et al., 2010; Blomert, 2011). These designs, in turn, are based on a large body of basic neuroscience research that suggests that symbolic integration should greatly enhance the response to matching, coincident stimuli; as the level of symbolic integration increases, then the response difference between matching and mismatching coincident stimuli should increase. For the Numberness task, we hypothesize that adults will show effects of integration, such that performance will be better when Arabic numerals and dot quantities match than when Arabic numerals and dot quantities mismatch. Moreover, this effect should only occur when the text shows a numeral, but not when the text shows a letter pair.

If symbolic integration exists, then the symbolic numeral shown on a stimulus could also influence participants’ perceptions of the stimulus’ dot quantity. Thus, a second group of participants was asked to estimate the number of dots shown in the Numberness stimulus images. We predicted that participants would show some bias in their dot quantity perceptions when paired with Arabic numerals, but not with letters. If participants showed a perceptual bias, then this could change what participants perceive as a symbolic and non-symbolic “match” in the Numberness task. Consequently, people might only show better performance on matching than mismatching trials in the Numberness task when these biases are taken into account.

Methods

Participants

One hundred one adults participated in the study. Participants were recruited through Amazon Mechanical Turk (AMT), an online, crowd-sourced participant pool. Recruiters post tasks on AMT, which workers can choose to complete; if the work is satisfactory, then the recruiter can grant approval and payment to the worker. All participants were required to be located in the United States, to have at least 50 approved tasks, and to have an approval rate of 95% or higher on the website, which is found to ensure high-quality AMT data (Peer, Vosgerau, & Acquisti, 2014). Sixty-five participants (36 female; age *M* = 38.2, *SD* = 13.7, range = 19-67 years; 57 with post-secondary education) completed the Numberness task for $0.50, and 36 participants (17 female; age *M* = 37.0, *SD* = 12.0, range = 18-63 years; 24 with post-secondary education) completed the Dot Cardinality task for $1.00. Payment was based on the average time taken to complete the task. Four participants from the Dot Cardinality group were excluded from analyses because they showed a misunderstanding of the task (e.g., typing repeated sequences of numbers or typing the numeric text instead of estimating the number of dots).

Materials

Stimuli Creation The dot clouds in the task stimuli were created using the MATLAB script written by Dehaene, Izard, and Piazza (2005). To control for perceptual differences in the stimuli, we created six images for each dot quantity tested in the tasks. The images were created by manipulating dot size and total area occupied by the dots, such that each dot quantity had images that used three different dot sizes and two different total areas. Double-digit Arabic numerals or letter pairs (12 numerals, 12 letter pairs) were superimposed at the center of each dot cloud (see Figure 1 for examples). Numerals ranged from 11 to 63, and dot quantities ranged from 7 to 95 dots.

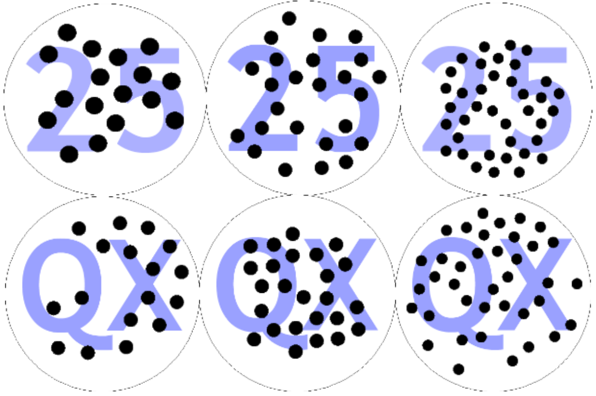

Figure 1: From left to right, examples of numeral and letter pair “num>dot,” “match,” and “num<dot” stimuli.

Numberness Task Participants were shown a series of images and asked to judge whether the image text showed a symbolic numeral or a letter pair. Participants responded by pressing "S" on a computer keyboard if the text was a numeral, and pressing "L" if the text was a letter pair. Each image was shown for 400 ms, and participants were given 1.5 s to respond. The task included 576 trials, separated into 6 blocks of 96 problems each. Of those 576 trials, 288 of the trials showed numerals and 288 of the trials showed letter pairs. Within the numeral trials, 72 showed images where the numeral and dot quantity matched ("match" trials), 72 showed images where the numeral was greater than the dot quantity at a 1.5 ratio ("num>dot" trials; e.g., 17 dots paired with the Arabic numeral "25"), 72 showed images where the numeral was less than the dot quantity at a 1.5 ratio ("num<dot" trials; e.g., 38 dots paired with the Arabic numeral "25"), and 72 showed images where only a numeral was shown ("filler" trials). For the letter text trials, letter pairs were randomly matched to numerals, such that specific letter pairs were always paired with the same dot quantities (e.g., "PN" was matched with the numeral "59," so both "PN" and "59" were always paired with dot quantities of 39, 59, and 89). Both numerals and their matched letter pair were always paired with the same sets of dot clouds, such that perceptual qualities of the stimuli were constant across the two conditions. Thus, within the letter text trials, there were also 72 trials of each type (match, num>dot, num<dot, filler), though the actual relations between the letters and dot quantities were arbitrary designations.

Dot Cardinality Task Participants were shown a series of images and asked to estimate the number of dots shown in the image. Participants typed in their estimates on a computer keyboard. Each image was shown for 400 ms, and participants were given an unlimited amount of time to respond. The purpose of this task was to determine the psychological magnitude of the presented dot quantities in the Numberness task; therefore, we reused the exact same stimuli from the Numberness task. Participants completed 432 trials: 144 involved "match" trials, 144 involved "num>dot" trials, and 144 involved "num<dot" trials. Half of each trial type contained numerals, and half contained letter pairs.

Procedure

After accepting the task on AMT, participants completed either the Numberness task or the Dot Cardinality task. If participants were given the Numberness task, they were required to achieve 80% accuracy on a short practice block of 10 trials before moving on to the real task.

Results

Numberness Task

Because we were primarily interested in the differences between match and mismatch (num>dot, num<dot) Numberness trials, we excluded all filler trials from the following analyses. Two additional trials were also removed because the stimulus images did not show correctly during those trials. This left a total of 430 trials for analysis. Trials with response times faster than 100 ms were excluded to eliminate trials in which participants had not processed the full stimuli. Trials in which participants ran out of time to respond (e.g., took longer than 1.5s to respond) were also excluded to control for external environmental issues that may have affected task performance.

To investigate the differences between matches and mismatches, we ran a 2 (text type: numeral, letter pair) X 3 (mismatch type: num>dot, match, num<dot) repeated-measures ANOVA on Numberness *accuracy*. Contrary to our symbolic integration hypothesis, we found no significant interaction between text type and mismatch type [$F(2, 128) = 2.13$, $p = 0.12$, $\eta_p^2 = 0.03$] (see Figure 3a). Overall, participants responded more accurately when images had a letter pair [$M = 0.93$, $SD = 0.08$] rather than a numeral [$M = 0.91$, $SD = 0.06$], [$F(1, 64) = 20.3$, $p < 0.001$, $\eta_p^2 = 0.24$]. There were no differences between the mismatch types [$F(2, 128) = 2.58$, $p = 0.08$, $\eta_p^2 = 0.04$].

A second 2 (text type: numeral, letter pair) X 3 (mismatch type: num>dot, match, num<dot) repeated-measures ANOVA was run on *median response times* on correct Numberness trials. There was a significant interaction with a Greenhouse-Geisser correction [$F(1.94, 124.2) = 13.6$, $p < 0.001$, $\eta_p^2 = 0.18$] (see Figure 4a). For numeral trials, there was a significant effect of mismatch type [$F(1.92, 123.1) = 18.9$, $p < 0.001$, $\eta_p^2 = 0.23$]. Post-hoc tests using a Bonferroni correction showed that match trials were significantly faster than both num>dot trials [$p = .02$] and num<dot trials [$p < 0.001$]. A mismatch effect was also seen for letter pair trials [$F(1.91, 122.1) = 5.86$, $p = 0.004$, $\eta_p^2 = 0.08$] in the opposite direction, such that match trials were significantly slower than num<dot trials [$p = 0.001$]. The response time results, but not accuracy results, provided partial support for symbolic integration.

Dot Cardinality Task

While the Numberness data did not show a strong integration effect, we wanted to see whether symbolic number information could influence non-symbolic number estimates by comparing participants' perceived dot quantity estimates to the objective dot quantities shown in the stimuli. Because several participants mistyped their estimates during the task, we calculated each participant's median estimate for each dot quantity to remove potential outliers.

Regressions were run on median dot estimates, using objective dot quantity as a predictor (estimated dot quantity = B_1*objective dot quantity + B_0). Separate regressions were run for each trial type (match, num>dot, num<dot for numeric text trials; match, num>dot, num<dot for letter pair trials), for a total of six regressions. If the symbolic numeral on each stimulus has no influence on participants' dot estimates, then the slopes of each regression should be equal.

The 95% confidence intervals of each regression's slope and intercept are shown in Table 1. For numeral trials, the slopes of the num>dot and num<dot trials were significantly

different from the slope of the match trials. Unexpectedly, for letter pair trials, the num>dot trial slope also significantly differed from the match trial slope, though differences between letter pair slopes were smaller than for numeral slopes (see Figure 2). The slopes for all six regressions were also significantly lower than a slope of 1, showing that participants are consistently overestimating small numbers of dots and underestimating larger numbers of dots shown in our stimuli.

Table 1: 95% confidence intervals for the Dot Calibration regression slopes and intercepts.

Trial Type	Slope CI	Intercept CI
Numeric text, match	0.74-0.83	3.75-6.99
Numeric text, num>dot	0.87-0.99	2.14-5.02
Numeric text, num<dot	0.61-0.68	6.44-10.30
Letter pair, match	0.65-0.74	4.66-7.94
Letter pair, num>dot	0.76-0.84	4.01-6.23
Letter pair, num<dot	0.65-0.74	5.99-10.85

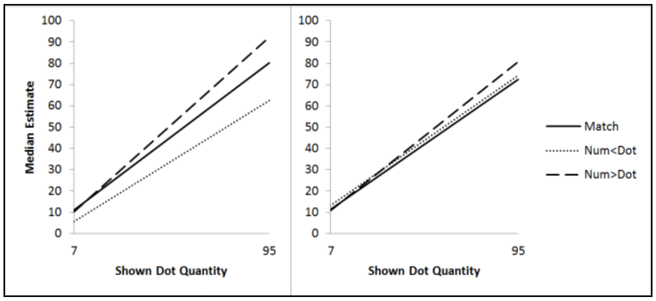

Figure 2: Mean regression equations of each trial type for numeral trials (left) and letter pair trials (right).

Numberness Task After Adjustment

Given the estimation biases in participants' dot quantity perceptions, we wanted to see whether adjusting the dot quantities in the Numberness task to reflect perceived dot quantities, rather than actual dot quantities as used in our previous analyses, would lead to greater differences between match and mismatch trials. A linear regression was run on the Dot Cardinality median dot estimates, using objective dot quantity as a predictor. The regression only used data from the letter text trials to avoid potential anchoring influences caused by the numeric text. Because the pairings between letter pairs and dot clouds were arbitrary, we collapsed across all three trial types. We derived the following equation from the regression to predict participants' perceived dot quantity, given the objective dot quantity on a stimulus: $Y = 0.72X + 6.62$. The perceived dot quantity was then used to re-categorize trials as match, num>dot, and num<dot trials.

We reran 2 (text type: numeral, letter pair) X 3 (re-categorized mismatch type: num>dot, match, num<dot) repeated-measures ANOVAs on the Numberness task's accuracy and response times. With a Greenhouse-Geisser correction, there was now a significant two-way interaction for *accuracy* [$F(1.33, 84.9) = 18.1$, $p < 0.001$, $\eta_p^2 = 0.22$] (see Figure 3b). For the numeral trials, match trials ($M = 0.95$, $SD = 0.09$) were significantly more accurate than num>dot trials ($M = 0.90$, $SD = 0.09$) [$p < 0.001$] and num<dot trials ($M = 0.91$, $SD = 0.08$) [$p = 0.001$]. There were no differences between match and mismatch trials for letter pair trials [$F(2, 128) = 1.52$, $p = 0.22$, $\eta_p^2 = 0.02$]. For *median response time*, there was also a significant interaction with a Greenhouse-Geisser correction [$F(1.42, 91.1) = 19.7$, $p < 0.001$, $\eta_p^2 = 0.24$] (see Figure 4b). For numeral trials, there was a mismatch effect [$F(1.39, 88.9) = 16.9$, $p < 0.001$, $\eta_p^2 = 0.20$] such that match trials were significantly faster than both num>dot [$p < 0.001$] and num>dot [$p < 0.001$] trials. There was no such effect for letter pair trials [$F(1.3, 85.1) = 3.32$, $p = 0.06$, $\eta_p^2 = 0.05$]. Thus, after adjusting for perceptual biases, match trials showed a consistent advantage over mismatch trials in both accuracy and response time. In addition, this advantage was unique to stimuli that showed Arabic numerals.

Discussion

The current study investigated whether adults would show evidence of symbolic integration when symbolic and non-symbolic number information was presented simultaneously. Specifically, we tested whether participants would perform better and more quickly when double-digit symbolic and non-symbolic number knowledge matched than when it mismatched. In the Dot Cardinality task, participants showed biases in their perceptions of our stimuli's non-symbolic number information, such that they consistently overestimated small quantities and underestimated large quantities. When these biases were used to determine when symbolic and non-symbolic information matched and mismatched in the Numberness task, then participants were more accurate and faster at making judgments about symbolic numerical stimuli when non-symbolic information matched than when it mismatched. No such effect occurred when participants were making similar judgments on letter stimuli. Accuracy differences between matching and mismatching trials did not appear when perceptual biases were not accounted for, suggesting that the perceived non-symbolic magnitudes are influencing performance rather than incidental features of the stimuli. Adults appear to naturally integrate symbolic and non-symbolic number knowledge, such that non-symbolic numerical information influences judgments about symbolic numerical stimuli.

We also found some evidence that estimates of non-symbolic quantities may be influenced by symbolic numerals. In the Dot Cardinality task, the slopes of participants' estimates were significantly different when dot quantities and symbolic quantities matched than when they mismatched. However, there were also some differences between slopes of letter pair trials, even though the matching and mismatching designations were arbitrary, suggesting that these slope differences may have been caused by something other than symbolic integration.

The consistent over- and under-estimation of numbers across both number and letter trials may also be evidence of symbolic integration. The numerals used in the Dot Calibration task ranged from 11 to 63, with 26 as its average value. This symbolic average may have biased participants' non-symbolic estimates across trials, which would fit with the results seen, such that dots in the 20s were perceived accurately, values lower than the 20s were overestimated, and values higher than the 20s were underestimated. Future studies could test this form of integration by varying the numerical range used in the task and investigating its effect on estimates.

Measuring Symbolic Integration

Our results highlight the potential importance of presenting symbolic and non-symbolic information simultaneously to detect symbolic integration. Previous studies have primarily utilized sequential presentations of symbolic and non-symbolic number information, which may not fully capture symbolic integration. Sequential designs may even tap into different cognitive processes, or require more cognitive resources to keep sequential information in mind, which could prevent these designs from uncovering integration in adults. Furthermore, our study shows that perceptual biases should be measured to determine how participants perceive non-symbolic stimuli. This is especially important for any paradigms utilizing the simultaneous presentation of symbolic and non-symbolic information, though it may also inform sequential paradigms (e.g., determining the perceived ratio between non-symbolic comparisons, or creating matched pairs of symbolic and non-symbolic trials).

Notably, the Numberness task used in the current study was not magnitude-related, as task judgments were removed from the magnitude of the stimuli. Yet, we still found magnitude-related results. Prior studies have often involved such quantity-related judgments (e.g., asking participants to compare two number quantities), which could prime people to attend primarily to either symbolic or non-symbolic numerical information. It would be informative to use the current study's co-occurring stimuli in a wider range of tasks that involve magnitude-related judgments to test the robustness of the matching and mismatching response differences.

Accounting for Individual Differences

In the current study, we adjusted the Numberness task data using the Dot Cardinality task data, but the data was collected in a between-subject design. Prior studies have shown that representational acuity of the ANS can vary greatly across individuals (Halberda, Mazzocco, & Feigenson, 2008), and that it continues to develop even into adulthood (Halberda, Ly, Wilmer, Naiman, Germine, 2012). Given the individual differences in perceptual biases of non-symbolic quantities, an average estimate of perceptual bias may not be sufficient to determine what each individual perceives as matching symbolic and non-symbolic numerical information. This may be an especially large problem in the current study because of the wide age range of participants. Ideally, one should determine how each individual perceives dot quantities, and then use that information to determine when symbolic and non-symbolic information is perceived as matching or mismatching. Future studies will measure both participants' symbolic integration performance and their perceptual biases, such that task performance can be individually adjusted.

In conclusion, the current study provides evidence for symbolic integration in adults. Non-symbolic numerical information appears to influence people's classification of double-digit Arabic numerals, even when that non-symbolic information is irrelevant for the judgment at hand. Our findings emphasize the importance of developing both types of number knowledge to best support performance in number-related tasks.

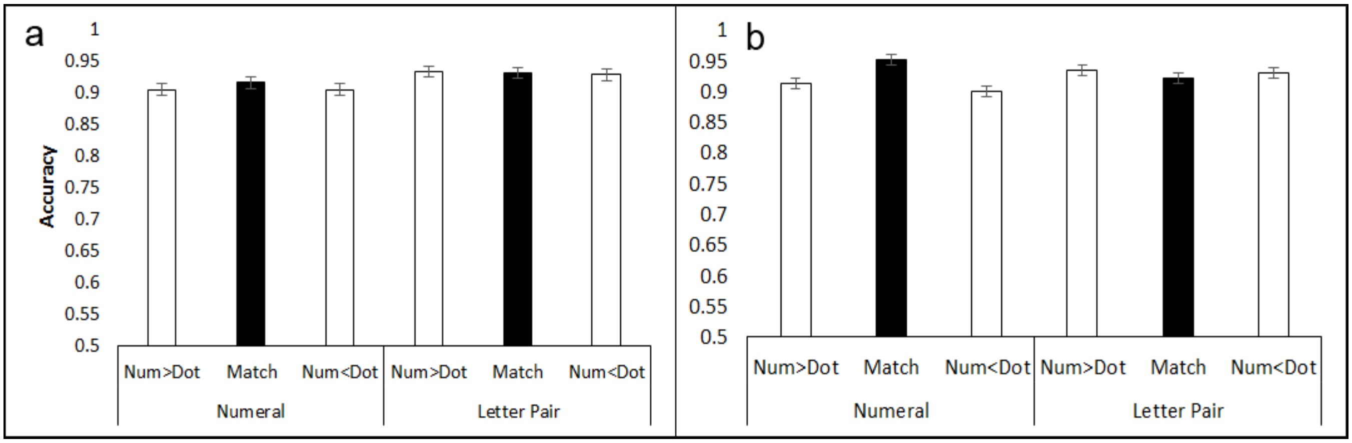

Figure 3: Numberness task accuracy (a) before adjustment and (b) after adjustment using the Dot Cardinality data with within-subject SE bars.

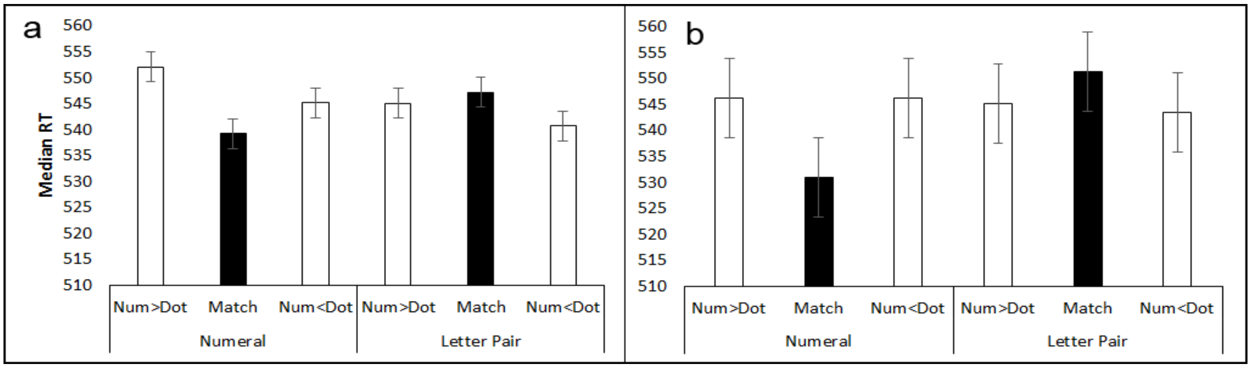

Figure 4: Numberness task response time (a) before adjustment and (b) after adjustment using the Dot Cardinality data with within-subject SE bars.

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