Task characteristics modulate unit-decade binding in two-digit number representation

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Abstract

Previous studies have found decomposed processes, as well as holistic processes, in the representation of two-digit numbers. The present study investigated the influence of task characteristics on such processes. Participants completed both magnitude and parity tasks in one of three instructional conditions, where they were asked to either consider two-digit numbers as a whole or to focus their attention on one of the digits only. In two experiments, we found that when participants were asked to consider the two digits as an integrated number, they always exhibited a unit-decade compatibility effect, indicating a failure of selective attention on the digit relevant to the given task. However, the mere presence of the neighboring digit is not sufficient condition for the compatibility effect: when participants were explicitly asked to ignore an irrelevant digit, their success/failure to selectively focus their attention on the relevant digit depended on task requirements. Further, computer mouse tracking indicated that the locus of the compatibility effect was related to late response-related processing. The results signify the deep involvement of top-down processes in unit-decade binding for two-digit number representation.

Keywords: Unit-decade compatibility, Selective Attention, Computer mouse tracking, Top-down processing

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When a child first learns to associate numerical digits with underlying numerical quantities, the transition from single-digit numbers to two-digit numbers presents a challenge. Indeed, two-digit numbers may be initially treated in such a fashion that the numbers 19 or 91 may not be discriminated from each other. Later on, however, the child learns about place value, where the specific location of each digit has its own value and even name (nine or ninety). With increasing experience, individuals learn to integrate the separate digits into holistic magnitudes (E. Klein et al., 2013; Mussolin & Noël, 2008). This leads to a natural question: Are the single digits of a two-digit number indeed merged into an inseparable internal magnitude code (i.e., holistic processing)? Or is it perhaps the case that people can flexibly form separate magnitude representations of the single-digits that comprise a two-digit number (i.e., decomposed processing)?

Evidence favoring decomposed processing was reported in the seminal study by Nuerk, Weger, and Willmes (2001), who found a unit-decade compatibility effect in comparison of two-digit numbers. When the decade and unit digits of one number were both smaller (or both larger) than both digits of the other number (e.g., 23 versus 45), reaction times (RTs) were faster than if the digits were unit-decade *incompatible* with each other (e.g. 29 versus 51). This finding indicates that participants make parallel comparisons of the decade and unit digits when comparing two-digit numbers, even though the decision can be made entirely by comparing the decade digits alone (see also Moeller, Nuerk, & Willmes, 2009).

The compatibility between the decade and unit digits can also explain the effect of overall distance that is commonly found in two-digit number comparison tasks (Dehaene, Dupoux, & Mehler, 1990; Hinrichs, Yurko, & Hu, 1981; Verguts & De Moor, 2005). For example, participants tend to respond faster when deciding whether 68 is larger than 55 than they do when deciding whether 61 is larger than 55, although a simple decade comparison is sufficient for deciding in both cases. Indeed, holistic processing may predict this distance effect, as the overall distance between 68 and 55 is larger than the overall distance between

61 and 55 (Moyer & Landauer, 1967). However, the distance effect observed here may instead be an artifact of unit-decade compatibility. Hence, measuring the distance effect alone seems to be inconclusive regarding the nature of two-digit representations (e.g. DeWolf, Grounds, Bassok, & Holyoak, 2014; for an extended discussion, see Nuerk, Moeller, Klein, Willmes, & Fischer, 2011).

The unit-decade compatibility effect has been replicated in many studies (Moeller, Klein, Nuerk, & Willmes, 2013; Moeller et al., 2009; Nuerk & Willmes, 2005). Recently, some investigations have focused on examining the factors that affect the attentional weight of the decade and unit digits. For example, the unit digit has been found to be more salient for German participants, who read the unit-digit first (e.g. 24 is said "four and twenty'") than for English, Spanish, or Italian speakers (Macizo, Herrera, Paolieri, & Román, 2010; Nuerk, Weger, & Willmes, 2005). So, the amount of attention allocated to the two-digit numerals" components may depend on the structure of the number words within a language. Also, Castronovo and Crollen (2011) found that the mode of presentation of the two-digit numbers (e.g., tens first, unit first, or simultaneously) could determine how much attention is paid to each component of the two-digit numbers. In addition, Macizo and Herrera (2011) manipulated the stimulus list by increasing the ratio of within-decade comparisons, which resulted in a larger unit-decade compatibility effect. This indicates that even a simple stimulus manipulation can induce participants to allocate more attention to the unit-digit.

Finally, in order to test if the processing of two-digit numbers depends also on task characteristics, Reynvoet, Notebaert, and Van den Bussche (2011) asked participants to perform either magnitude or parity judgments on two-digit targets preceded by masked primes. The briefly-presented primes contained one of the target digits in either a task-congruent ($3\# \rightarrow 37$) or a task-incongruent ($\#3 \rightarrow 37$) position. The first digit mainly mediated the priming effects (e.g., faster RTs for task-congruent primes) in a magnitude task, presumably because the decade digit has the largest predictive value when comparing magnitudes (see also Ganor-Stern, Tzelgov, & Ellenbogen, 2007; Ratinckx, Brysbaert, &

Fias, 2005). The opposite pattern was found in the parity task, probably due to the importance of the unit digit in such a task.

In summary, most recent studies agree that the magnitude of two-digit numbers is not only represented as one holistic entity, but also decomposed for its components (units and decades). Participants' failure to compare the decade digits only while ignoring irrelevant unit digits (the unit-decade compatibility effect) served as the key marker in this notion of decomposed processing (Moeller et al., 2013). Note that in these previous studies, participants were asked to consider the two-digit numbers as holistic mathematical units (e.g., to decide if two-digit number is smaller or larger than 55). The unit-decade compatibility effect measured their ability to process the two-digit number as integral mathematical unit (holistically) or not (decomposed processing). In the present study, however, we tackle the compatibility effect from another direction: we explicitly ask participants to deal with two-digit numbers in a specific decomposed manner. Will they be able to exclusively process the relevant digit, while simultaneously ignoring the irrelevant digit?

Two recent studies imply that the mere *presence* of adjacent digits is enough to elicit automatic processing of the irrelevant digit. Nuerk, Bauer, Krummenacher, Heller, and Willmes (2005) used an Eriksen flanker task, in which three identical distractor stimuli appeared on both left and right sides of a single-digit target. They found that when distractor stimuli led to the same response as the target, responses were faster than when they were associated with a different response, demonstrating that participants processed the magnitude of the irrelevant adjacent digit. Similarly, Kallai and Tzelgov (2012) presented single-digit numbers as three digit strings with zeros in two of three positions. They manipulated the position of the nonzero digit, presenting it in either the hundreds position, the decade position, or the unit position. Even though participants were asked to ignore the zeros, Kallai and Tzelgov found that the position of the nonzero digit had a significant effect on response patterns, even though the position was irrelevant to the task. Once again, such a result indicates that participants may automatically form representations of the magnitude

of multiple digits.

Note that both of the above studies used a magnitude task only. In addition, the location of the adjacent digit(s) was not controlled. For example, the distractor stimuli in Nuerk et al. (2005) were presented on both the left and right sides of the target. Therefore, these studies do not allow us to fully investigate the influence of specific task characteristics, or the interaction between task (i.e., magnitude or parity) and the side (left or right) of the adjacent digit. Nevertheless, these studies imply that at least in *some* cases, (a) the mere presence of some digits next to each other is sufficient for participants to process them automatically even without an explicit instruction, and (b) that participants are aware of the place-value of a digit even if it is irrelevant to the task.

To summarize, systematic studies into the influence of task instructions on unit-decade binding in two-digit numbers remain scarce, and the debate on its specific role is ongoing. In our study, we aimed to explore the effect of task instructions on the processing of two-digit numbers by using the unit-decade compatibility effect as a marker of decomposed processing. Our second aim was to examine the flexibility and boundary conditions under which these binding effects appear. Precisely, we asked whether the mere presence of two digits next to each other was sufficient for participants to treat them as a two-digit number. Or, perhaps, is it necessary to explicitly define our stimuli as a two-digit number (through task instructions) in order for such unit-decade binding to occur?

To address these questions, we asked participants to separately perform magnitude and parity tasks with two-digit numbers. Within each task, we gave three different types of instructions: *overall*, *decade-only*, and *unit-only*. In the overall condition, the participants' task was to consider the stimuli as a "two-digit number". Thus, for the magnitude task, the specific instruction was to decide if the two-digit number was smaller or larger than 55. For the parity task, the specific instruction was to decide if the two-digit number was odd or even. The overall condition served as a benchmark for our other critical decomposed conditions. In the two decomposed instructional conditions, participants were explicitly

instructed to pay attention to only the decade or the unit digit. In the magnitude task, they were to decide if the single relevant digit was smaller/larger than 5, and in the parity task, they were to decide whether the single digit was odd/even. Importantly, in these decomposed instructional conditions, the adjacent digit always served as a task-irrelevant stimulus and was unassociated with the correct response required for the target digit. Hence, we were especially interested in observing whether participants could ignore the irrelevant digit and focus their attention exclusively on the target digit.

In our experiments, we explicitly manipulated the *congruency* of the digits in each stimulus. The definitions of congruent/incongruent depended on task. For example, in the parity task, trials were congruent when both the task-relevant and task-irrelevant digits required the same response (i.e., both digits odd or both even, such as 37 or 46). Parity trials were incongruent when the two digits required opposite responses (i.e., one digit odd and the other even, such as 78). Congruency on the magnitude task was defined similarly; trials were congruent when both digits required the same response (i.e., both digits smaller or larger than 5, such as 78 or 23) and incongruent when digits resulted in opposite responses (i.e., one digit smaller than 5 and the other larger, such as 28 or 73). In light of this congruency manipulation, we hypothesized that our instructional conditions (overall, decade-only, or unit-only) would modulate attentional focusing towards the irrelevant digit only when the irrelevant digit is relevant for completion of a specific task. As a consequence, in the magnitude task, we predict that greater interference will occur when the distractor is in the decade position (i.e., when participants are asked to pay attention to only the unit digit). In contrast, in the parity task, we expect more pronounced interference from neighbors in the unit position (i.e., when participants are asked to pay attention to only the decade digit).

We test these predictions in two experiments that use similar stimuli and procedures but vary the response mode. In Experiment 1, participants categorized parity/magnitude status of a target digit using left-right keypress responses, from which we measured overall response times (RTs). In Experiment 2, participants categorized parity/magnitude by

moving a mouse cursor from a central "start" area to a target areas positioned in the upper left or right corner of the screen. This allowed us to record the streaming x, y-coordinates of the computer mouse movements during the decision process. Such data will provide evidence of competition between response options that cannot be easily detected from patterns of RTs alone. Moreover, integrating these two approaches allows us to effectively test the generality of our predictions across different response modes.

Experiment 1

Method

Participants. Sixteen students (two left-handed males, mean age 22.1 years) from Ariel University Center participated in three experimental sessions in exchange for partial course credit.

Stimuli and apparatus. The stimulus set consisted of all two-digit numbers in the range 11-99, excluding numbers with 5 or 0 in it (e.g., 40 or 51). These sixty-four two-digit numbers were replicated, resulting in 128 trials in a single block. Half of the stimuli were smaller than 55 and half were larger than 55. Half of the numbers were odd and the other half were even. Finally, the number of congruent and incongruent numbers was equal in both tasks. The stimuli were presented in their Arabic form and appeared in black Times New Roman font (size 30) at the center of the screen on a white background of a 17-in. (43 cm, 1024 X 768 pixel resolution) monitor. Responses were made on a standard QWERTY keyboard, with all keys covered except A (left hand responses) and L (right hand responses). Reaction times and accuracy were recorded with SuperLab 2.0.

Procedure. Data were collected in a dimly lit room with the participant seated approximately 50 cm from the center of the screen. In each trial, a fixation cross appeared for 500 ms on a blank screen and was then followed by a randomly selected two-digit number. In the overall condition, the participant's task was to decide if the two-digit number is smaller or larger than 55 (magnitude task) or if the two-digit number is odd or even (parity

task). In the decade and the unit conditions, the participant's task was to decide if the relevant digit (leftmost digit or rightmost digit) is smaller or larger than five (magnitude task), or if the relevant digit is odd or even (parity task). The left/right response keys served for odd/even and smaller/larger responses, according to the previously agreed response rule. Each stimulus number stayed on the screen until a response was made, and the next trial began 500 ms later.

A planned break of 15 minutes between tasks was given, while a short 5 minute break separated between the two subsequent blocks of response rules. Each session took approximately 50 minutes to complete, and approximately one week separated between sessions.

Results

Participants completed a total of 24574 experimental trials. We discarded 1010 trials that contained an incorrect response (error rate = 4.11%). Further, we removed an additional 624 trials for which response time was below 200 msec and above six median absolute deviations (MAD) from the overall median RT (median RT = 561 msec, MAD = 148.26 msec) (Leys, Ley, Klein, Bernard, & Licata, 2013). This cleaning procedure resulted in retaining a total of 22940 trials (93.40% of original trials).

Unit-decade congruency was defined in a conceptually similar way for both magnitude and parity tasks: a two-digit number was defined as *congruent* if both decade and unit digits led to an identical response. The number was defined as incongruent if the digits yielded conflicting responses. For instance, the two-digit number 34 was considered as congruent in the magnitude task (since both decade and unit are less than 5), but as an incongruent in the parity task (since 3 is odd, but 4 is even).

In order to compare the congruency effect between tasks and the different instruction conditions we first ran a two-way ANOVA for the overall condition with factors of task and congruency only (see Figure 1). We found a main effect of congruency, $F(1, 15) = 14.30$,

$p = .002$, $\eta_p^2 = .488$. As shown in Figure 1, responses to incongruent numbers in the overall condition were slower for both the magnitude and parity tasks. Neither the main effect of task [$F(1, 15) = 2.52$, $p = .133$] nor the interaction between task and condition [$F(1, 15) = 1.40$, $p = .256$] reached significance. Hence, the compatibility effect did not differ between the magnitude and parity tasks.

We next aimed to check if the compatibility effect differed between the decade and unit conditions. To this end, we ran another ANOVA with independent variables of task, congruency, and the two crucial instructional conditions (decade only, unit only). There was a significant main effect of task, $F(1, 15) = 12.51$, $p = .003$, $\eta_p^2 = .455$. On average, the magnitude task was 30 ms faster than the parity task. In addition, there was a significant main effect of congruency, $F(1, 15) = 26.10$, $p < .001$, $\eta_p^2 = .635$. Responses to incongruent numbers were 20 ms slower than responses to congruent numbers. There was no main effect of instructional condition, $F(1, 15) = 0.02$, $p = .880$, $\eta_p^2 = .002$.

There was also an interaction between task and condition, $F(1, 15) = 13.32$, $p = .002$, $\eta_p^2 = .470$, and this interaction depended on congruency condition, as signified by the significant three-way interaction between task, instruction condition, and congruency, $F(1, 15) = 16.09$, $p = .001$, $\eta_p^2 = .518$. As shown in Figure 1, when participants were asked to focus their attention on the decade digit and ignore the unit digits, there was no effect of congruency in the magnitude task, $t(15) = 0.24$, $p = .811$. However, there was a large effect of congruency in the parity task, $t(15) = 4.43$, $p < .001$, indicating that participants suffered from intrusions from the irrelevant unit digit. By contrast, when participants were asked to pay attention to only the units digit, a large congruency effect appeared in the magnitude task, $t(15) = 4.38$, $p = .001$, but this effect was only marginally significant in the parity task, $t(15) = 2.28$, $p = .038$. No other terms in the ANOVA model were statistically significant (all F values less than 1.38).

Discussion

The pattern of unit-decade compatibility effects (which we term as *congruency* effects here) appears to depend heavily on specific task characteristics. For the magnitude task, we found a congruency effect in the overall condition but not in the decade-only condition of the magnitude task. Since the same stimulus set was presented in both conditions, the only difference was whether we asked participants to compare the two-digit number to 55 (the overall condition) or to compare the left digit to 5 (the decade condition). In both conditions, participants could have successfully completed the task by focusing only the leftmost digit. However, by asking participants to compare to 55, (and thus implicitly defining the two adjacent digits as a two-digit number), we induced participants to process the irrelevant digit as well, thus resulting in the observed congruency effect.

A different pattern emerged in the parity task. There, we again found a congruency effect in the overall condition but not in the *unit* condition. Again, the same stimulus set was presented in both conditions and the only difference was whether we instructed the participant to classify the parity of the two-digit number (the overall condition) or of the rightmost digit (the unit condition). In each case, the task could have been successfully completed by attending to only the rightmost digit. However, the congruency effect was found in the overall condition but not in the unit condition.

So far, these findings can be interpreted as follows. As in past studies, when participants were instructed to consider the two digits as a holistic two-digit number (the overall condition), they automatically processed both digits, as was demonstrated by the observed unit-decade compatibility effect in both magnitude and parity tasks. However, such a failure of the selective attention was not always found when participants were explicitly instructed to consider the two adjacent digits in a decomposed manner (decade and unit conditions). The absence of the equivalent Stroop-like interference effect in the decade condition of the magnitude task and the unit condition of the parity task indicate that processing of the irrelevant adjacent digit is not always obligatory. Indeed, it appears that

specific task characteristics can modulate the unit-decade binding processes in two-digit number representation.

Experiment 2

In Experiment 2, we tested the generality of our findings by replicating the basic procedure of Experiment 1, but instead of using button presses, we had participants indicate their decisions via a computer mouse click. This allowed us additionally to track participants' hand movements during their decisions, giving a window into the evolution of the decision process (Freeman & Ambady, 2009; Freeman, Dale, & Farmer, 2011; Spivey, Grosjean, & Knoblich, 2005). Such an approach has been used in several previous studies investigating the formation of numerical representations (Faulkenberry, 2014, 2016; Faulkenberry, Cruise, & Shaki, 2017; Faulkenberry, Cruise, Lavro, & Shaki, 2016; S. Santens, Goossens, & Verguts, 2011; Song & Nakayama, 2008)

Method

Participants.   Sixty undergraduate students (52 female, mean age = 24.1 years, age range 18 to 57) participated in this experiment in exchange for partial course credit in their psychology courses. One participant was removed from further analysis due to an experimenter error during data collection, leaving 59 participants total. The experiment was reviewed and approved by the institutional review board at Tarleton State University.

Apparatus.   The experiment was coded and delivered using the MouseTracker software package (Freeman & Ambady, 2010). All experimental trials were presented on a 20 inch iMac desktop computer with a screen resolution of 1,280 x 1,024 pixels and a refresh rate of 60 Hz. Input was captured via a Dell optical mouse connected via USB. Participants were seated in a manner such that there was a distance of approximately 60 cm between the computer display and the participants' eyes. Participants were instructed to hold the computer mouse in a manner which was comfortable. All participants held the mouse in the right hand, positioned slightly to the right of center on the computer table.

We ran the MouseTracker program on the iMac using a virtual Windows XP environment via Parallels. As per the recommendations of M. H. Fischer and Hartmann (2014), we disabled the "dynamic acceleration" option and lowered the speed of the mouse movements on the screen to the second-lowest possible speed in the mouse settings dialog. This is done to prevent quick and erratic mouse movements, resulting in a smooth and more reliable record of participants' hand movements. The resulting displacement ratio of the mouse to screen movement was 1 cm to 100 pixels.

Stimuli and procedure.   We designed computer mouse tracking versions of the same two-digit number tasks described in Experiment 1, with stimuli consisting of the 64 two-digit numbers described in Experiment 1. Participants completed a magnitude task and a parity task according to one of three randomly assigned instructional conditions: overall ($n = 19$), decade-only ($n = 20$), or unit-only ($n = 20$). Participants in the overall condition were told that they would be presented with a single two-digit number. Participants in the decade-only condition were presented with "two digits next to each other", and were instructed to pay attention to only the *left* digit. Participants in the unit-only condition were given similar instructions, except that they were instructed to pay attention to only the *right* digit.

All participants completed 256 experimental trials, consisting of a block of 128 trials of a magnitude task and block of 128 trials of a parity task. These task blocks were completed in counterbalanced order. Half of the participants began with the magnitude task block, whereas the other half began with the parity task block. For participants in the overall condition, the magnitude task required participants to choose, as quickly as possible, whether the presented two-digit number was less than 55 or greater than 55. Participants in the decade-only and unit-only conditions were instructed to choose whether the relevant single digit (left or right, respectively) was less than 5 or greater than 5. The parity task required participants to choose whether the presented number was even or odd. For participants in the overall condition, they were instructed to decide whether the two-digit number was even

or odd, whereas participants in the decade-only and unit-only conditions were instructed to decide whether the relevant single digit (left or right, respectively) was even or odd.

Each trial began with a blank screen presented for 500 ms, followed by a screen that displayed the appropriate response labels at the top left and right of the screen, respectively, as well as a single "Start" button at the bottom center of the screen. Each response label was presented in Arial font with point size 24. Response labels depended on task; for the magnitude task, the response labels were "Small" and "Large", whereas for the parity task, the response labels were "Even" and "Odd". Within a single-task block (128 trials), the left-right ordering of the response labels was switched halfway through the block (i.e., after the completion of 64 trials).

Once the "Start" button was pressed, one of the 64 stimulus numerals appeared in the center of the screen, presented in Times New Roman font with point size 30. Participants then clicked on the correct response option; while doing so, the software recorded the streaming (x, y) coordinates of the computer mouse approximately 63 times per second. The left-right position of the correct response option was counterbalanced across trials within each block.

For incorrect responses, the program displayed an "X" for 2000 ms. To ensure that trajectories reflected online processing, participants were encouraged to begin their movements as early as possible and were warned if initiated movement later than 400 ms following number pair presentation. This instruction is customarily included in mousetracking studies so that trajectories reflect the dynamics of a decision process rather than simply reflecting the kinematics of a response choice after the choice has already been made (Freeman & Ambady, 2009; Spivey et al., 2005).

In total, participants completed two blocks of each of two tasks, resulting in 4 repetitions of the 64 number stimulus set. Thus, each participant completed 256 experimental trials in a single 30 minute session.

Results

Participants completed a total of 15104 experimental trials. We discarded 182 trials that contained an incorrect response (error rate $= 1.20\%$). As in Experiment 1, we removed an additional any trials for which response time was below 200 msec and above six median absolute deviations (MAD) from the overall median RT (median RT $= 1125$ msec, MAD $= 209.05$ msec); this resulted in the removal of 166 additional trials. In all, our cleaning procedure resulted in retaining a total of 14756 trials (97.70% of original trials).

Time analyses.   For each trial, the MouseTracker software recorded two time-based performance measures. The first of these, reaction time (RT), is defined as the total time elapsed from when the participant began a trial by clicking the START button until the target mouse click. The second measure, initiation time (Init), is defined as the time elapsed from the initial mouse click of the START button until the onset of mouse movement. From these two measures, we calculated movement time (MT), which indexes the temporal duration of mouse movement, by subtracting RT - Init on each trial.

Movement times.   Similar to the approach taken in Experiment 1, we aimed to first compare the congruency effect between tasks and the different instruction conditions by first conducting a two-way ANOVA on movement times (MTs) for the overall condition with factors of task and congruency only. We found a main effect of congruency, $F(1, 18) = 14.70$, $p = .001$, $\eta_p^2 = .450$. As shown in Figure 2, incongruent numbers in the overall condition resulted in longer mouse movement durations for both the magnitude and parity tasks. Neither the main effect of task ($F(1, 18) = 3.36$, $p = .084$, $\eta_p^2 = .157$) nor the interaction between task and condition ($F(1, 18) = 0.01$, $p = .929$) were significant.

Next we aimed to test whether the congruency effect differed between the decade and unit conditions. We submitted MTs to a three-way ANOVA with independent variables of task, congruency, and instructional condition (restricted to the decade only and unit only conditions). Overall, the results were similar to those with RTs in Experiment 1. There was a significant main effect of task, $F(1, 38) = 9.84$, $p = .003$, $\eta_p^2 = .206$, indicating that MTs in

the parity task were longer than those in the magnitude task. There was also a significant main effect of congruency, $F(1, 38) = 34.78$, $p < .001$, $\eta_p^2 = .478$, where MTs for incongruent numbers were longer than MTs for congruent numbers. There was no main effect of instructional condition, $F(1, 38) = 1.12$, $p = .296$, $\eta_p^2 = .029$.

The task x condition interaction we observed in Experiment 1 with RTs did not reach significance with MTs in Experiment 2, $F(1, 38) = 3.72$, $p = .061$, $\eta_p^2 = .089$. However, there was an interaction between task and congruency, $F(1, 38) = 34.78$, $p < .001$, $\eta_p^2 = .478$, and this interaction depended on instruction condition, as signified by a significant three-way interaction, $F(1, 38) = 8.45$, $p = .006$, $\eta_p^2 = .182$. As shown in Figure 2, when participants were asked to focus only on the decade digit and ignore the unit digit, there was no effect of congruency on MTs in the magnitude task, $t(19) = -0.43$, $p = .669$. However, we did observe a large congruency effect in the parity task, $t(19) = 3.87$, $p = .001$, indicating a failure of selective attention on the parity task. In contrast to Experiment 1, when we asked participants to pay attention to only the units digit, a large congruency effect appeared in both the magnitude task, $t(19) = 3.56$, $p = .002$, and the parity task, $t(19) = 6.62$, $p < .001$. No other terms in the ANOVA model were statistically significant (all F values less than 1.57).

Initiation times. Mouse initiation times were submitted to a three-way ANOVA with factors of congruency, task, and instruction condition. There was a significant main effect of instruction condition, $F(2, 56) = 3.59$, $p = .034$, $\eta_p^2 = .114$. Pairwise independent samples t-tests indicated that participants in the overall condition took significantly longer to initiate computer mouse movements than participants in the unit condition, $t(37) = 2.96$, $p = .005$. However, there were no significant differences in initiation times between the overall condition and the decade condition ($t(37) = 1.78$, $p = .084$) or between the decade and unit conditions ($t(38) = 0.69$, $p = .493$). Further, we observed a significant main effect of congruency, $F(1, 56) = 5.97$, $p = .018$, $\eta_p^2 = .096$, with faster initiation times on incongruent trials. No other terms in the ANOVA model were significant (maximum $F = 0.98$).

Trajectory analyses. Computer mouse trajectories were measured by recording the streaming x, y - coordinates of the computer mouse during each trial. The raw trajectories were then pre-processed and normalized in MouseTracker (Freeman & Ambady, 2010) to allow for ease of analysis across different experimental conditions. Specifically, all trajectories were rescaled onto a standard coordinate space of [-1,1] x [0,1.5] and normalized via linear interpolation to consist of exactly 101 timesteps. This step allowed for direct comparison of trajectory curvatures, indexed via area under the curve (AUC). Since MouseTracker computes AUC for each trial by summing the areas of 100 trapezoids that comprise the area between the trajectory path and the ideal straight line between the start box and the response box, it is essential that the trajectories each be comprised of the same *number* of timesteps.

To see how the magnitude and parity decisions unfolded over time, we plotted average mouse trajectories as a function of congruency and instruction condition. Trajectories for the magnitude task are depicted in Figure 4, and trajectories for the parity task are depicted in Figure 5.

As with our other dependent measures, we tested how the congruency effect (as manifested in trajectory curvatures) differed between the three instructional conditions. We first submitted AUCs for participants in the overall condition to a two-way ANOVA with independent variables of task and congruency. As can be seen in Figure 6, we observed a significant main effect of task, $F(1, 18) = 7.08$, $p = .016$, $\eta_p^2 = .282$, indicating that curvatures in the parity task were greater than those in the magnitude task. There was also a significant main effect of congruency, $F(1, 18) = 17.18$, $p = .001$, $\eta_p^2 = .488$, where curvatures for incongruent numbers were greater than curvatures for congruent numbers. There was also a small, but marginally significant interaction between task and congruency, $F(1, 18) = 4.48$, $p = .048$, $\eta_p^2 = .199$.

Next we submitted AUCs in the decade-only and unit-only conditions to a three-way ANOVA with independent variables of task, congruency, and instructional condition. There

was a significant main effect of instruction, $F(1, 38) = 6.97$, $p = .012$, $\eta_p^2 = .155$, indicating that curvatures in the parity task were greater than those in the magnitude task. There was also a significant main effect of congruency, $F(1, 38) = 39.09$, $p < .001$, $\eta_p^2 = .507$, where curvatures for incongruent numbers were greater than curvatures for congruent numbers. There was also a main effect of task, $F(1, 38) = 8.46$, $p = .006$, $\eta_p^2 = .182$, reflecting greater curvatures for the parity task than for the magnitude task.

Further, we observed a significant interaction between congruency and instruction, $F(1, 38) = 11.28$, $p = .002$, $\eta_p^2 = .229$, and this interaction depended on task, as signified by a significant three-way interaction, $F(1, 38) = 6.55$, $p = .015$, $\eta_p^2 = .147$. As shown in Figure 6, participants who were asked to focus only on the decade digit and ignore the unit digit exhibited no effect of congruency on AUCs in the magnitude task, $t(19) = -0.38$, $p = .708$. However, as we observed with RTs (in Experiment 1) and MTs (in Experiment 2), we did observe a large congruency effect in the parity task, $t(19) = 2.69$, $p = .014$. Finally, when participants were asked to pay attention to only the units digit, a large congruency effect appeared in both the magnitude task, $t(19) = 4.49$, $p < .001$, and the parity task, $t(19) = 3.72$, $p = .001$. No other terms in the ANOVA model were statistically significant (all F values less than 0.31).

Discussion

Experiment 2 provides further evidence that varying task instructions may cause participants to modulate their focus of attention to the surrounding digits, depending on their respective relevance for accurate task completion. As in Experiment 1, the overall condition yielded similar pattern of congruency effects across the two tasks (magnitude and parity). But, different patterns occurred when participants were asked to focus only on one digit. For example, when the task required magnitude comparison on *unit* targets, participants' mouse trajectories were initially biased towards the irrelevant digit in the decade position, resulting in relatively large reach curvatures and longer MTs on incongruent

compared to congruent trials. In contrast, when the task required magnitude comparison on *decade* targets, the absence of curvature and MT differences between congruent and incongruent trials implies that the reaching movements were immune to interference from the irrelevant digit in the unit position. On the other hand, when the task required parity judgment, we observed interference effects (longer MTs, greater AUCs) with varying strengths from incongruent primes in both positions, suggesting that irrelevant digits in both decade and unit positions can bias participants' spatial attention towards competing response options.

It is perhaps interesting that movement initiation was relatively immune to our congruity manipulation. However, we did find a significant effect of task condition on movement initiation. That is, participants showed longer initiation times over the course of overall condition (where they focus on the whole digit) as compared to decomposed conditions (where they focus on a single component). The differences in initiation times suggest that the speed with which a response was initiated was influenced by perceptual complexity of the stimulus number. It may be the case that target digits with longer length (i.e., two digits versus a single digit) might increase perceptual load, which in turn increases the duration of motor preparation and initiation. This interpretation of the data would be consistent with previous research indicating that initiation time and reach curvature originate from two dissociable processes (e.g., Erb, Moher, Sobel, & Song, 2016; Ruitenberg et al., 2016; Strauss, Woodgate, Sami, & Heinke, 2015). Specifically, it is thought that initiation times might be driven by an early action planning stage that is tied to cue-related processes, whereas MT and AUC might reflect mainly top-down (controlled) processes which provide for revision and correction of the decision during the movement execution phase. Altogether, our analysis of movement dynamics echoes and extends the results obtained using the traditional keypress paradigm in Experiment 1. Possible implications of these findings for understanding the time-course of two-digit number representation are addressed in the General Discussion.

General Discussion

The aim of the present study was to investigate unit-decade bindings in two-digit numbers and examine how they are created as function of task-context. To this end, we asked participants to perform parity or magnitude tasks while paying attention to a specific digit (either the decade digit or the unit digit). Critically, we manipulated congruency of the irrelevant "prime" digit with respect to the specific task. In the two experiments, participants in the magnitude task experienced a large degree of interference from an incongruent prime in the decade digit when asked to pay attention to only the unit digit. On the other hand, when participants were asked to pay attention to only the decade digit, no such interference from the incongruent prime in the unit position was observed. A different pattern emerged in the parity task, where interference effects from incongruent primes were observed in both instructional conditions. Thus, changes in task context are sufficient to divert attentional resources to a specific position within a two-digit number, indicating that (1) people form decomposed representations of two-digit numbers, and (2) unit-decade binding is not always obligatory. This finding is consistent with previous research indicating that the amount of attentional weight given to the processing of decades or units can be regulated by means of task context (e.g., Castronovo & Crollen, 2011; Macizo & Herrera, 2011; Reynvoet et al., 2011). Moreover, such evidence constrains the syntactic structure model of two-digit numbers which predicts that compatibility should be mainly affected by numbers' decade digits but not by numbers' unit digits (Ganor-Stern et al., 2007). Altogether, these results combine with previous studies to suggest that two-digit number representations are adaptive to manipulations of experimental context.

The asymmetry of the unit-decade compatibility effects observed in the present study can be interpreted as a consequence of the dynamic reorganization of attentional weights that are associated with the different roles that decades and units play in a given task. For example, when performing magnitude comparison in two-digit numbers, task context dictates that participants should focus a large portion of their attention on the decade digit,

as the decade must necessarily be processed in order to perform the comparison task. This increased attentional weight toward the decade digit apparently persists when people are asked to focus only on the unit digit. However, when people are asked to focus only on the decade digit, no such interference occurs. It is important to stress that the present study goes beyond previous experiments that examined unit-decade compatibility because here we show that compatibility between two-digits can emerge even when participants are asked to pay attention to a single component of a two-digit number.

Another goal of the present study was to establish the point in the stimulus processing stream at which the unit-decade conflict first emerges and how it is resolved over time. We did so by analyzing the early and late kinematic parameters afforded by computer mouse tracking. In this analyses, we detected two distinctive influences with time-varying patterns on response decisions. The first notable influence appeared in the earliest stages of movement with initiation times. Specifically, the speed with which participants initiated their hand movements was highly influenced by complexity of the string of digits (holistic vs. decomposed), but not by their congruity conditions. In contrast to this, the congruency effect from incongruent primes was evident relatively late in movement, as trajectories showed more attraction toward the incorrect response option on incongruent than on congruent trials.

We next discuss the implications of these findings for understanding how two-digit number processing unfolds over time. One possible explanation is that the initiation time measure in our study might reflect an early processing stage at which the identity of the digits is already coded but not yet assigned to the corresponding unit and decade positions within the number. Only at a later phase of movement execution, as more information accumulates, participants start associating digit identities with a specific position within the number, resulting in increased attraction of response trajectories toward the incorrect response on incongruent trials (see Dotan & Dehaene, 2013 for a similar argument with number-to-position task). This interpretation of the data fits well with a dynamic view of

decision-making which describes decision process as a continuous competition between response alternatives in which initial choice can be revised at any time during the movement as soon as new information becomes available (Spivey et al., 2005). This explanation would also be consistent with earlier findings favoring a distinction between effects of action planning and online control (Erb et al., 2016; Ruitenberg et al., 2016; Strauss et al., 2015).

Moreover, our findings may provide an empirical validation for recent conceptual distinction introduced by Nuerk, Moeller, and Willmes (2014) assuming that the place-value system for multi-digit numbers is subserved by different steps. A first step, place-identification, refers to the earliest stages of perceptual encoding at which relevant symbols (Arabic digits) are differentiated based on their positional identity (i.e., units, tens, etc), without activating their corresponding semantic values. At the subsequent step, place-value activation, the semantic values associated with those digit positions become activated, leading to the empirically observed compatibility effect. A third step, place-value computation, is recruited in particular situations when place-value properties are required to solve a multi-digit arithmetic task, and thus is not relevant for the present discussion. The difference found between early and late measures of mouse movement is consistent with the above suggestion that early visual identification processing – at least in part – precedes the position coding processes that takes place later and causes the congruency effect. One possible reason for this is that place-value coding relies on availability of binding and maintenance processes in working memory, which takes more time to retrieve, thereby, cascading it to later stages of processing. Another possibility is that competition between response alternatives takes place only when overt response starts, thus becoming visible only during a response-related stage of processing. Further research is needed to disentangle between these alternative possibilities.

Next, we provide a theoretical framework to explain how task instructions may modulate unit-decade binding in two-digit number comparison. For this purpose, we use a variant of dual-route model that has been shown to account for a number of key findings in

the number domain, such as the SNARC effect and the size congruity effect (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; S. Santens et al., 2011). According to this model, congruity originates from parallel activation of two independently operating routes that interact at the decision level. The first (unconditional) route automatically processes task-irrelevant stimulus information and primes the associated response, while the second (conditional) route codes for task-relevant stimulus information and is activated intentionally on basis of task instructions. Changing the instructions (task-related route) leads to a change in the pattern of weights that determine which stimulus features are bound to response features. The functional differences between the mapping of relevant and irrelevant stimulus features to responses (on the basis of instructions) is sufficient to create different types of congruency. To see this, suppose that a task entails a magnitude comparison of the unit digit only. Participants are then presented with stimulus "78", for which (in this specific task) decade places are irrelevant. In this case, both routes (conditional and unconditional) activate the same response, since with a compatible number like "78", both digits are larger than referent value of 5. The result is that a response is executed relatively quickly. However, when a new task instruction is given emphasizing parity judgment, pre-existing links between stimulus features and responses are re-bound to form a new meaning. More specifically, now both routes converge on opposing responses, as now "78" is an incompatible number, since the two digits have opposite parity status. The result here is that RTs are increased. The main point is that the proposed model accounts for two key characteristics responsible for the compatibility effect in our study: namely, the modulatory effects of instructions and its response-related origin. However, to account for the observed asymmetry in our data, the model needs to make additional assumptions with respect to how strongly the dominant stimulus values (decades or units) are associated with response options (magnitude or parity) such that the gradient of connections is increasing to one of the response labels but decreasing to the other.

Finally, we discuss some possible limitations of our study. First, despite the efforts to

achieve comparability by applying the same stimulus sets and mostly equivalent procedural details to parity and magnitude tasks, the present study does not rule out a potential contribution of mechanistic differences between these tasks. At least in the context of the SNARC effect, previous researchers have pointed out that these two tasks are unequivalent with respect to working memory resources (Dijck, Gevers, & Fias, 2009; Herrera, Macizo, & Semenza, 2008). Additionally, it could be argued that in situations where subjects shift between tasks, the history of previous experience with, for example, a magnitude comparison task, may remain active and later interfere with a new task goal of judging parity. Under these circumstances, it is unclear whether the pattern interference effects are driven by activation of the current or previously seen context when switching between two tasks (Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). To counteract for such task-transition effects, we further validated our methodological approach in Experiment 2 by manipulating the instruction assignment for the magnitude comparison and parity-judgment tasks *between* rather than within subjects. This procedure helped to ensure that distractor category conflicted with the target category on only one dimension of task context (i.e., whether the task was parity or magnitude). The results of Experiment 2 were largely similar to those of Experiment 1, providing further evidence that components of a two-digit number become bound due to instructional context rather than via an *a priori* representational binding.

To summarize, our study demonstrates the role of task context for unit-decade binding in two-digit number representation. We have demonstrated that processing both components of two-digit numbers is obligatory only if participants have been asked to consider the two-digit number as an integral mathematical whole. However, if participants have been explicitly asked to pay attention to one digit only, their ability to ignore the irrelevant adjacent digit depends on the task requirements. This asymmetrical pattern in selective attention indicates the deep involvement of top-down processes in two-digit number representation.

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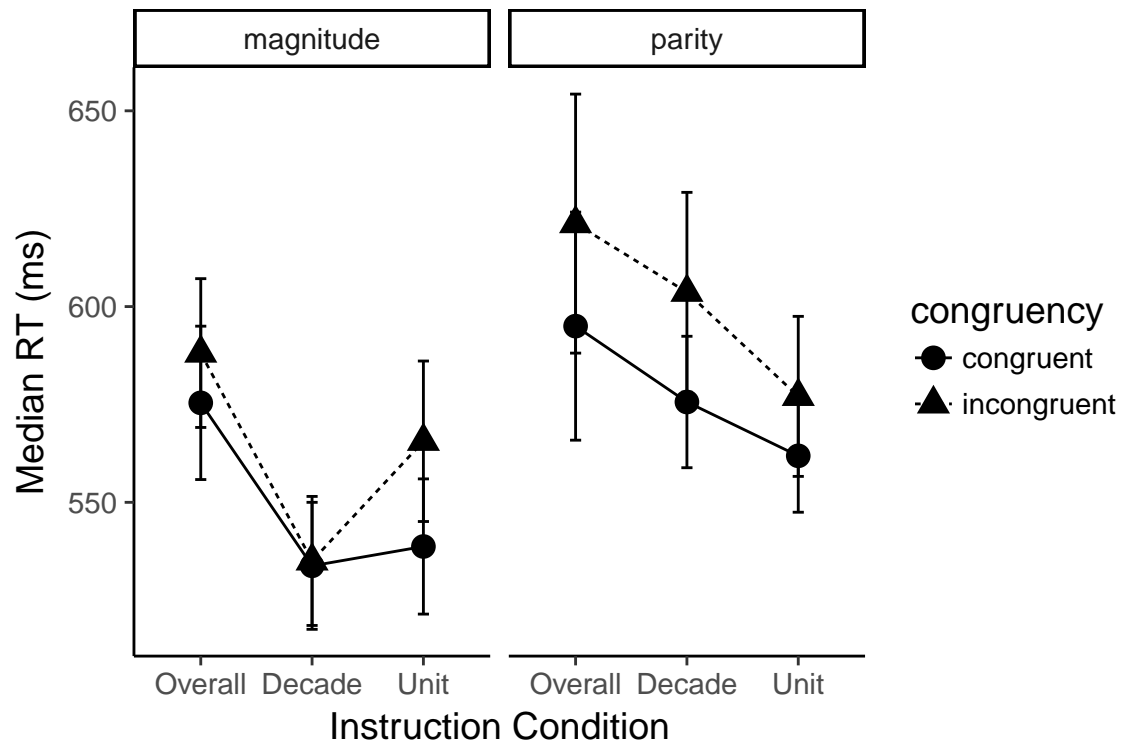
Figure 1. Median RTs as a function of congruency (congruent, incongruent), instruction condition (overall, decade only, unit only), and task (magnitude, parity). Error bars represent within-subject 95% confidence intervals as recommended by Morey (2008).
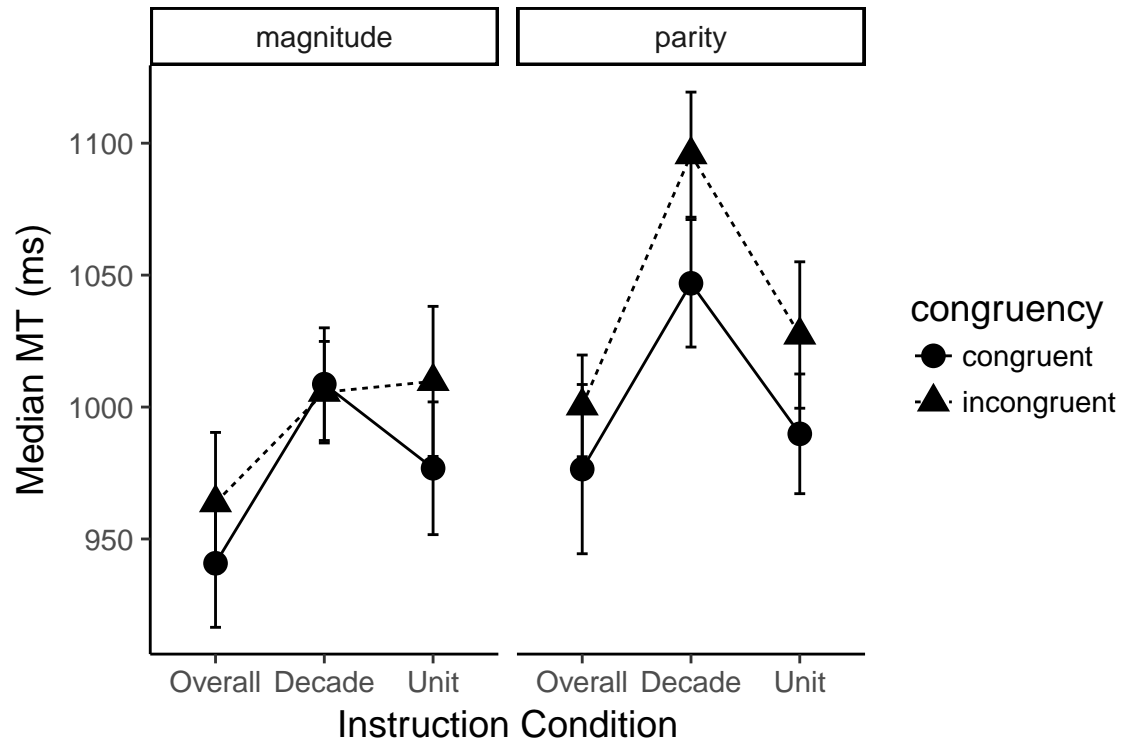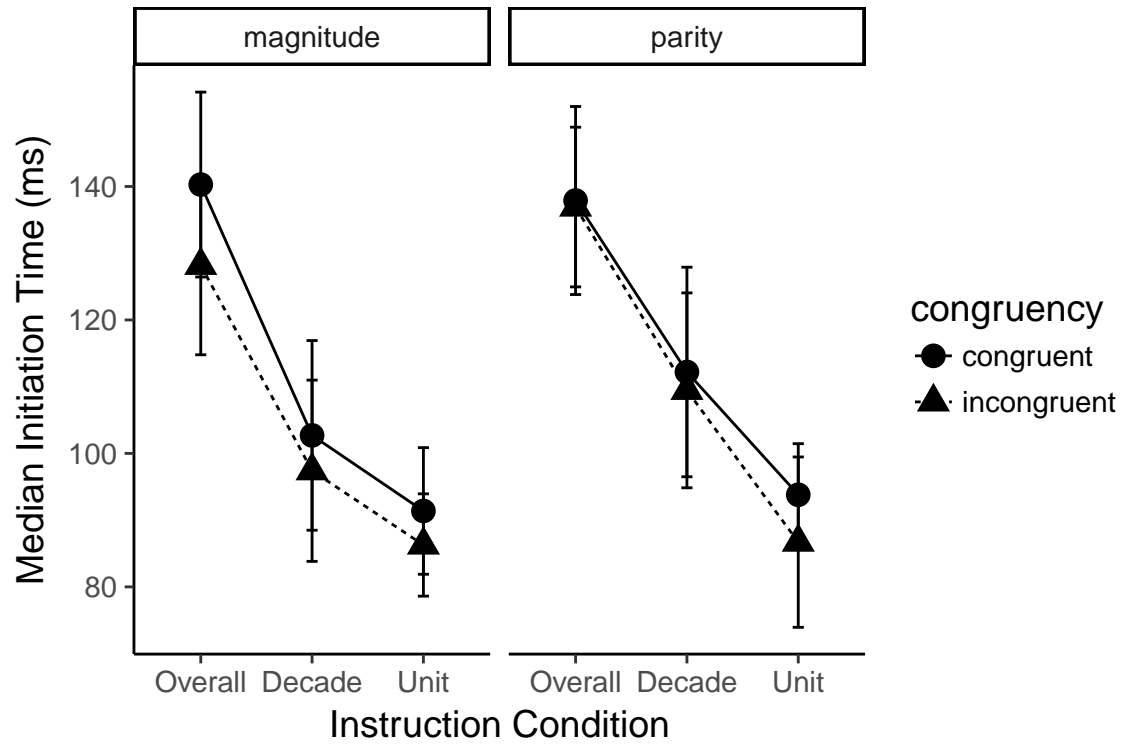
Figure 2. Median mouse movement times (MTs) as a function of congruency (congruent, incongruent), instruction condition (overall, decade only, unit only), and task (magnitude, parity). Error bars represent within-subject 95% confidence intervals as recommended by Morey (2008).
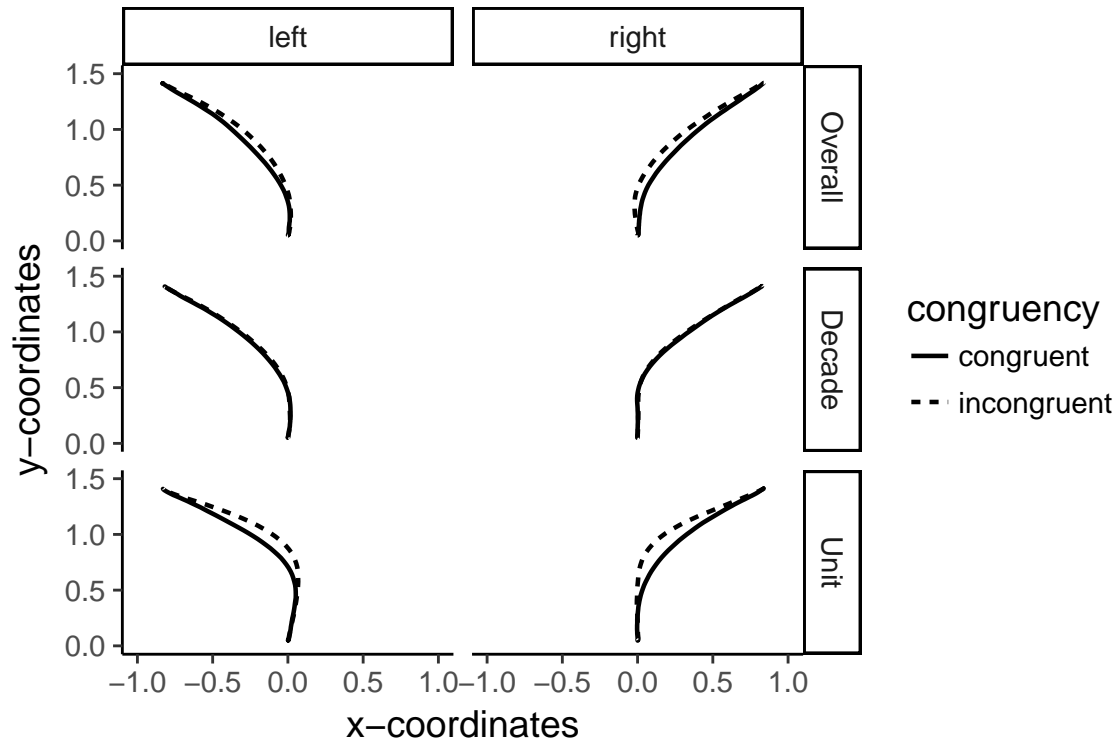
Figure 3. Median mouse initiation times as a function of congruency (congruent, incongruent), instruction condition (overall, decade only, unit only), and task (magnitude, parity). Error bars represent within-subject 95% confidence intervals as recommended by Morey (2008).

Figure 4. Average normalized mouse trajectories for the magnitude task, presented as a function of congruency (congruent, incongruent), instruction condition (overall, decade only, unit only), and response side (left, right).
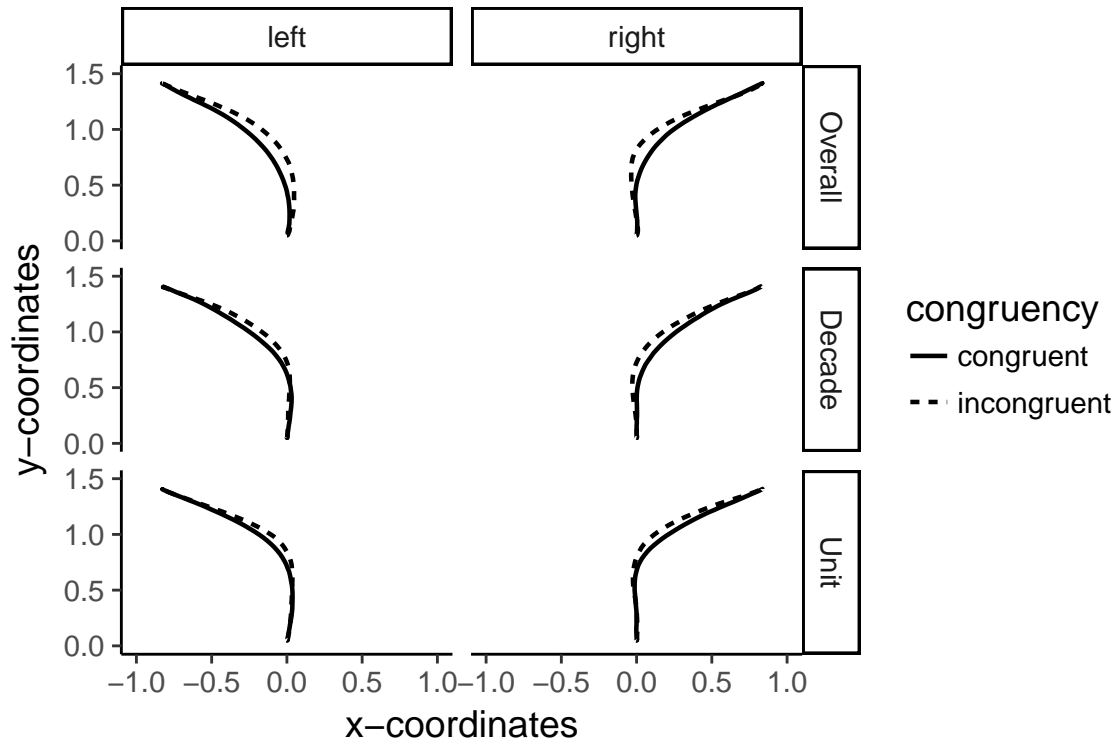
Figure 5. Average normalized mouse trajectories for the parity task, presented as a function of congruency (congruent, incongruent), instruction condition (overall, decade only, unit only), and response side (left, right).
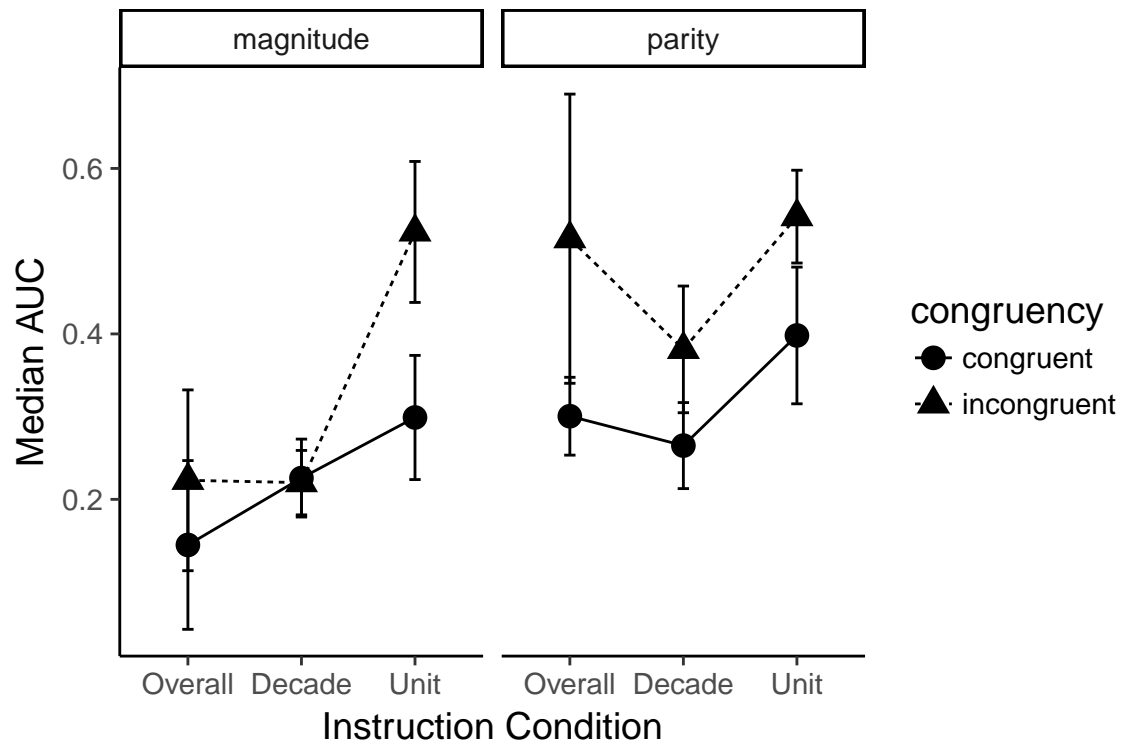
Figure 6. Median area-under-the-curve (AUC) as a function of congruency (congruent, incongruent), instruction condition (overall, decade only, unit only), and task (magnitude, parity). Error bars represent within-subject 95% confidence intervals as recommended by Morey (2008).