REPRESENTATION OF TWO-DIGIT NUMBERS: THE ROLE OF TASK CHARACTERISTICS

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Abstract

Previous studies found holistic and decomposed processes in the representation of two-digit numbers (e.g. Nuerk, Weger & Willmes, 2001). The present study investigated the influence of task characteristics on such processes. Participants were explicitly instructed to either consider two-digit numbers as a whole or to focus their attention on one of the digits only. Evidence favoring the hybrid model was found only when instructions encouraged treating the digits as two-digit numbers. Otherwise, processing irrelevant digits was dependent on the natural task requirements. The results signify the deep involvement of top-down processes in the representation of two-digit numbers. Moreover, the task-dependent asymmetry of the results challenge the syntactic explanation suggested for the decade-unit asymmetry.

When the individual first learns to identify single digits, two-digit numbers are treated in an analytical fashion, so the numbers 19 or 91 have the same values of its two components. Later on, the place value of multi-digits is learned, and the specific location of each digit has its own value and even name (nine or ninety). With increasing experience, people are encouraged to integrate the separate digits into holistic magnitudes. Are single digits of a two-digit number indeed perceptually blended into an inseparable internal magnitude code? Or alternatively, perhaps people are always aware of the constituent values of two-digit numbers.

Three competing theoretical models are suggested to account for the nature of two-digit representations: a holistic, a decomposed, and a hybrid model (Dehaene, Dupoux & Mehler, 1990; Moeller, Huber, Nuerk & Willmes, 2010; Verguts & De Moor, 2005). In its basic form, the holistic model posits that numbers are processed holistically and that people encode two-digit number as an integrated representation before (or along with) executing any comparison task. The decomposed model suggests that the magnitude representations of decade and unit digit are activated separately, either sequentially or in parallel. Finally, the hybrid model suggests that both decomposed as well as holistic representations of number magnitude are activated.

Surprisingly, the multi-dimensional aspect of two-digit numbers has almost never been tested with the traditional methodologies of selective attention. A single study by Fitusi and Algom (2006) explicitly required participants to respond selectively to one of the digits while ignoring the other one. In a Garner paradigm (Garner, 1974), they found that participants could focus their attention on the decade digit only, without suffering interference from an incompatible unit digit. However, participants could not ignore the decade digit when explicitly being asked to do so, demonstrating an asymmetry between both digits of two-digit numbers. Similar asymmetry was found by Ganor-Stern et al., 2007, who argued, "that the syntactic roles of the digits were represented" (p. 483).

The present study has two aims. First, we explored what are the conditions required to turn two adjacent digits into a single two-digit number. Is the mere presence of two digits next to each other sufficient for participants to treat them as a two-digit number? Alternatively, is defining two digits as a two-digit number important? In order to test the above question, we asked participants in one condition to decide the magnitude or parity of two-digit numbers as

a whole. In the two complementary conditions, participants were explicitly instructed that the target is the decade or the unit digit only. Looking at the distance effect in these conditions makes it possible to approach the question of two-digit representation from the holistic aspect.

Second, the experimental design permits an examination of the perception of two-digit numbers from the composite side as well. Do people always process the two components of two-digit numbers? Moreover, we are interested in finding whether the decade-unit asymmetry is due to the syntactic roles of the digits (Fitusi & Algom, 2006; Ganor-Stern et al., 2007; Ratinckx, Brysbaert & Fias, 2005) or to the task requirements. Note: parity tasks naturally demand focusing on the unit digit only, while it makes sense to look at the decade digit (first) in comparison tasks. Hence, comparing the compatibility effect between tasks, as well as the decade and unit distance effects, is a test case of the origin of the decade-unit asymmetry.

Method

Participants: Sixteen students (two left-handed males, mean age 22.1 years) from Ariel University Center participated in three experimental sessions, for 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 twice, 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. The stimuli 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.

Design: There were two task-order conditions (magnitude task first, parity task first), three target conditions in each task (holistic, decade, unit) and two response rules in each condition (Even-left or Even-right, and small-left or small-right) for each condition, resulting in twelve experimental blocks. This factorial combination (128 trials in each block X 12 blocks) resulted in 1536 trials in total per participant.

Participants performed the holistic conditions of both tasks in the first session. Then, they performed the decade conditions and the unit conditions separately in the two subsequent sessions. The two response rules for each experimental condition were always done in two subsequent blocks. The task order, the decade and unit conditions order, and the response rules were counterbalanced across participants but were kept fixed along the experiment for each participant. Order of trials was randomized in each block.

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 holistic condition, the participant's task was to decide if the number is smaller or larger than fifty-five (magnitude task), or if the 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 (decade or unit) 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. The stimulus 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 (in the first meeting) and target conditions (in the second and third meetings) 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.

Analysis: RT analyses are presented first, followed by error analyses. Correct RTs were trimmed by accepting responses within ±3 standard deviations, leaving 98.8% of the correct responses for statistical evaluation.

Definition of congruency was determined in a conceptually similar way for magnitude and parity tasks: a two-digit number was defined as congruent if its decade and unit digits lead to an identical response. The number was defined as incongruent if its digits yield conflicting responses. For instance, the two-digit number 34 was considered as congruent in the magnitude task but as an incongruent in the parity task.

Results

Figure1 provides a summary of an ANOVA on RTs, with task (magnitude, parity), the three target conditions (holistic, decade, unit), and congruency (congruent and incongruent numbers). On average, the magnitude task was 29.2ms faster than the parity task [$F(1,15) = 14.44$, $MSe = 2830.3$, $p < 0.01$]. The main effect of target condition was also found reliable: participants performed the holistic condition (644.9 ms) much slower than the decade (609.1 ms) and unit (606.8 ms) conditions [$F(2,30) = 6.01$, $MSe = 4870.5$, $p < 0.01$]. In addition, responding to incongruent numbers was slower (628.7 ms) than to congruent numbers (611.9 ms) [$F(1,15) = 16.56$, $MSe = 815.5$, $p < 0.01$], demonstrating a general failure of selective attention.

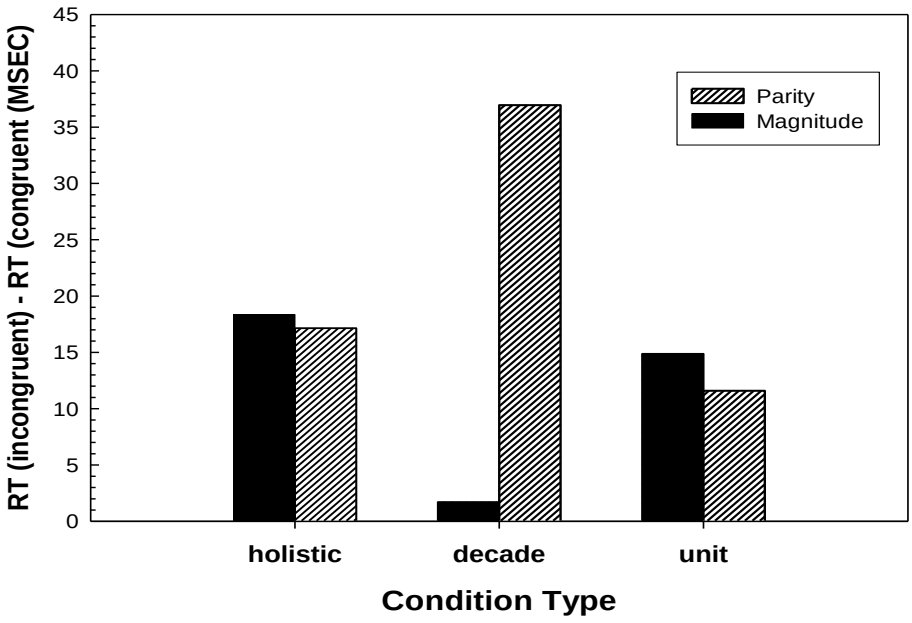

Figure 1. Mean response times (RTs) of congruent numbers subtracted from mean RTs of incongruent numbers (compatibility effect) as a function of condition for comparison and parity tasks.

Did selective attention to the relevant dimension differ between tasks and target conditions? This question was answered by the significant three-way interaction of task,

target condition, and congruency [$F(2,30) = 6.06$, $MSe = 309.9$, $p < 0.01$]. As shown in the left panel of figure 1, a significant failure of selective attention was demonstrated in the holistic condition for both magnitude ($t(15) = 2.26$, $p<0.05$) and parity ($t(15) = 1.77$, $p=0.05$). However, when they were asked to focus on the decade digits and to ignore the unit digits (middle panel), participants could turn their attention to the decade digit in the magnitude task ($t(15) = 0.214$, $p>0.05$), but they suffered from intrusions from irrelevant unit digits in the parity task ($t(15) = 5.25$, $p<0.01$). By contrast, interference from the irrelevant decade digit (right panel) was demonstrated in the magnitude task ($t(15) = 2.79$, $p<0.01$), but absent in the parity task ($t(15) = 1.62$, $p>0.05$). None of the two-way interactions turned out to be significant.

The failure of selective attention in some conditions reflects composite processes in those cases. In order to explore possible latter holistic processes (e.g. the hybrid model), we submitted the absolute values of the decade, unit, and global distances to a stepwise multiple regression, in each condition of the comparison task. Regression analyses were highly predictive in all three conditions ($r=0.895$, $r=0.831$, and $r=0.66$, in the holistic, decade, and unit conditions, respectively. All $p<0.001$). Most important, however, is the fact that global distance was the only significant predictor in the holistic condition ($b=-0.895$, $p<0.001$), the decade distance was the only significant predictor in the decade condition ($b=-0.831$, $p<0.001$), and the unit distance was the only significant predictor in the unit condition ($b=-0.66$, $p<0.001$). This pattern of results remained when the logarithms of decade, unit, and global distances were used (e.g. Dehaene et al., 1990; Nuerk et al., 2001).

Finally, the error data generally mirrored the above effects, thereby indicating an absence of a speed–accuracy effect. Overall, error rates were 4.09%, with significantly more errors in the parity task (5.61%) than in the comparison task (2.59%) [$F(1,15) = 5.91$, $MSe = 73.99$, $p < 0.05$]. The main effect of congruency was significant as well, with more errors for the incongruent numbers (4.93%) than for congruent numbers (3.26%) [$F(1,15) = 18.87$, $MSe = 7.1$, $p < 0.001$]. Finally, the three-way interaction of task, condition, and congruent was highly significant [$F(2,30) = 7.86$, $MSe = 5.54$, $p < 0.001$], mirroring again the pattern obtained for RTs: the highest error-rate was found for incongruent numbers in the unit condition (comparison task) and in the decade condition (parity task).

Discussion

Following previous findings of the holistic and decomposed processing of two-digit numbers (e.g. Ganor-Stern, Pinhas & Tzelgov, 2009; Nuerk et al., 2001; Zhang & Wang, 2005), the present study investigated the role of task and condition requirement in such processes.

This study has two important results. First, when introducing two adjacent digits as a two-digit number (e.g. the holistic condition), we found global distance effect and compatibility effect, similarly to previous findings (e.g. Dehaene et al., 1990; 1993; Nuerk et al., 2001). Such results probably reflect holistic and decomposed processes, as was suggested by the hybrid model. By testing participants in the decade and unit conditions, we demonstrated, for the first time, that holistic and even decomposed processes are not obligatory. As the absent of global distance and compatibility effects imply, the mere presence of two digits together is not sufficient to generate holistic or decomposed processes. Instead, participants should be instructed to consider the two digits as a two-digit number.

Second, the asymmetrical pattern of the participant's selective attention indicates the deep involvement of the top-down processes. In the parity task, participants could ignore an

irrelevant decade digit but failed to ignore an irrelevant unit digit, probably because in a typical parity task, people have to pay attention only to the unit digit. The opposite pattern was found in the comparison task, most likely because this task usually demands focusing (mostly) on the decade digit.

This later result is in agreement with previous studies (Fitusi & Algom, 2006; Ganor-Stern et al., 2007), which found decade over unit advantage in comparison tasks. However, they concluded that "this pattern of results supports the components with syntactic structure model" (Ganor-Stern et al., 2007, p. 488), in which more weight is given to the decade as compared with the unit digits. The present findings serve as a kind of double dissociation between tasks, and demonstrate how the syntactic structure depends on the natural requirements of the task.

Finally, exploring the distance effects in a comparison task reveals that the global value of two-digit numbers was a significant predictor in the holistic condition only. As is expected from the absence of compatibility effect in the decade condition, the unit and the global distance effects were not significant predictors. Interestingly, the unit distance effect was the only significant predictor in the unit condition, although the failure of selective attention in this condition implies that participants processed the decade digits. Still, the distance effect of decade digits did not emerge, apparently demonstrating dissociation between compatibility and distance effects. It is possible that an irrelevant decade digit is categorically processed (small or large), generating the compatibility effect. However, the exact value of the digit is not projected on the mental number line, resulting in an absence of distance effect.

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