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Young Adults with Developmental Dyscalculia Do Represent and Process Number Magnitude

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Abstract

The mental representation of numbers in long-term memory was compared in university students diagnosed with developmental dyscalculia with minimal comorbidity and healthy control participants. The participants were selected based on their performance in MATAL - a standard computer-based test battery for the diagnosis of learning disabilities in students in tertiary education in Israel. All participants performed a numerical size comparison task and a physical size comparison task of numbers differing in their physical and numerical size. Both groups showed normal intentional processing of numerical magnitude as marked by regular distance and size effects. Furthermore, both groups did not differ in automatic processing of numerical size as indicated by the normal and equally increasing (with intra-pair distance) size congruity effect and the equal space-number association of response codes effect. The implications of these findings for understanding the source of dyscalculia are discussed.

Keywords: developmental dyscalculia, mental number line, automatic processing, distance effect, size effect, end effect, SNARC effect

Introduction

Six to eleven percent of the population present significant difficulties in learning mathematics (von Aster & Shalev, 2007), referred to as developmental dyscalculia (DD). DD is reflected in several different numerical functions such as spontaneous focusing on numbers (Hannula, Lepola, & Lehtinen, 2010), comparing non-symbolic numerical quantities (e.g., dot arrays; Piazza et al., 2010), processing numbers symbolically (e.g., in Arabic notation; Stock, Desoete, & Roeyers, 2010), or linking non-symbolic representations to symbols such as Arabic numerals (Bugden & Ansari, 2011; Rubinsten & Henik, 2005; for review see Kaufmann et al., 2013).

Children with DD are far behind their classmates in a wide range of numerical tasks; they have difficulties in retrieval of arithmetical facts (Geary, 1993), using arithmetical procedures (Russell & Ginsburg, 1984; Shalev & Gross-Tsur, 2001), and they use immature problem solving strategies (e.g., using finger counting; Jordan, Hanich, & Kaplan, 2003). Mathematical difficulties have been shown to be more damaging to career prospects than reading deficiencies (Parsons & Bynner, 2005). Beddington et al. (2008; see also Butterworth, Varma, & Laurillard, 2011; Goswami, 2008) argued that untreated learning difficulties can lead to immense costs for society. Our study draws from our general interest in the mental representation of numbers. We assume that representations stored in long-term memory, which are relatively not affected by intentional strategies, store the "primitives" of a given cognitive system (see Tzelgov, Ganor-Stern, Kallai, & Pinhas, in press). Numerical primitives are the building blocks for generating more complex numerical entities such as multi-digit and negative numbers, or fractions (when required to do so). The purpose of this study is to assess and compare the representation and processing of numerical primitives in young adults with and without developmental dyscalculia.

The metaphor frequently used to describe the mental representation of numbers is **the mental number line (MNL).** It assumes that numbers, being symbolic representations of magnitude, are mapped onto a line. Consistent with this metaphor is the **distance effect,** first reported by Moyer and Landauer (1967), which refers to the negative correlation between the response time (RT) of the comparison of two numbers and the numerical distance between them. Restle (1970) reported that the **size effect** reflects Weber’s law, according to which, given a constant distance between two numbers, their numerical comparison time increases with their (mean) numerical magnitude. This in turn is consistent with a compressive mapping function of numbers onto the MNL.

The notion of the MNL is used both to describe the semantic representation of numbers in long-term memory and representations emerging in working memory in accordance with specific task requirements. As already mentioned, we are interested in the **representations** in LTM—the mental units stored in long-term memory and used to generate additional representational units that can be viewed as mental primitives. Such primitives can be accessed by automatic processing (Kallai & Tzelgov, 2009; Tzelgov et al., in press). Tasks that require deliberate processing (e.g., intentional comparisons of numerical size) reflect not just internal features of the mental representations but also the strategies applied on *them* in order to perform the task optimally ((Tzelgov & Ganor-Stern, 2005). In contrast, automatic processing that occurs without conscious monitoring allows access to the MNL in semantic memory (Bargh 1989, 1992; Tzelgov, 1997). Notice that consistent with memory retrieval theories of automaticity (Logan, 1988; Perruchet & Vinter, 2002), we are assuming that automatic processing does not require (at least not intentional) additional processing of whatever was retrieved from memory.

Two markers of automatic processing of numerical size are frequently used. The first marker is the size congruity effect (SiCE). The SiCE is obtained when participants perform physical size comparisons on stimuli varying also in their numerical size. Notice that physical size comparisons refer to the size of the numerals that represent numerical magnitude. The processing of these numerical magnitudes is automatic in the sense of not being part of the task requirements. The SiCE refers to the increased latency in the incongruent condition (e.g., 3 5) as compared to the congruent (e.g., 3 5) one (Henik & Tzelgov, 1982). The SiCE was observed in many studies when single-digit (1D) numbers were used as stimuli, thereby validating the claim that 1D numbers are primitives. Furthermore, consistent with the metaphor of the mental number line, the SiCE increases with the intra-pair distance along the irrelevant numerical dimension (Cohen-Kadosh & Henik, 2006; Schwarz & Ischebeck, 2003; Tzelgov J., Yehene, Kotler, & Alon, 2000). Consistent with the assumption of the compressed representation along the MNL, the SiCE is smaller for pairs of larger numbers (Pinhas, Tzelgov, & Guata-Yaakobi, 2010).

Two processes are apparently involved when adults compare magnitudes. One is an analog comparison process, which produces the distance effect (Moyer & Landauer, 1967). The other is the activation of end stimuli (i.e., objects representing the smallest and the largest magnitudes in the set), which results in the **end effect**—faster processing of pairs including the end stimuli of a set (Banks, 1977). Leth-Steensen and Marley (2000) proposed a formal model that shows how the two processes result in an arrangement of the mental representation of objects in order of their magnitudes. Pinhas and Tzelgov (2012) proposed that the two-process model of Leth-Steensen and Marley also applies to automatic processing of numbers. They attributed the monotonous increase of the SiCE with the intra-pair numerical distance (e.g., Henik & Tzelgov, 1982; Tzelgov et al., 2000) to an analog comparison process that is dominated by the distance effect. In addition, the faster processing of pairs containing end stimuli was suggested to enlarge the SiCE due to earlier availability of numerical magnitude information (Schwarz & Ischebeck, 2003), and to attenuate the modulation of the SiCE by the intra-pair distance. This phenomenon was coined the automatic end effect (AEE) by Pinhas and Tzelgov and was shown to exist for 0, and for 1 in its absence, but not for larger numbers; that is, the AAE was absent when 2 was the smallest number in the set. This finding is important by showing the special status of 1 (and zero) as the semantically smallest numbers stored in long-term memory (Tzelgov et al., in press). It is also consistent with the special status of 1 as hypothesized by Leslie, Gelman, and Gallistel (2008). Recently Goldman, Tzelgov, Ben-Shalom, and Berger (2013) provided further support for the claim that both the analog comparison process and the AEE are involved in automatic comparison of numbers by showing that the emergence of the AEE developmentally precedes the automatization of the end effect.

An additional marker of automatic processing in the numerical domain is the spatial numerical association of response codes (henceforth, SNARC) effect (Dehaene, Bossini, & Giraux, 1993). The parity task has become the most frequent task that has been used to investigate the SNARC effect (Wood, Nuerk, Willmes, & Fischer, 2008). Usually in the parity task, participants are asked to indicate the parity status of numbers with bimanual responses. The effect is indicated by a negative correlation between the difference of the right-hand key and left-hand key response latencies when responding to a given number, and the magnitude of that number. Such a correlation is consistent with the assumption that the MNL spreads from left to right. Up until a while ago there were no reports of SNARC effects in Hebrew readers. Recently Zohar-Shai, Tzelgov, Karni, and Rubinsten (in press) showed not only that the effect exists in Hebrew readers but also that its direction is identical to the one obtained in readers of languages written from left to right (e.g., English), that is, the MNL spreads from left to right.

In the present study we compared the mental representation of numbers in long-term memory (LTM) of university students diagnosed with DD and healthy control participants. Our study draws from our general interest in the mental representation of numbers. Many studies have been directed at higher-level, school-like concepts and have focused on general cognitive functions such as problems in working memory (Geary, 1993) or deficits in attention systems (Shalev, Auerbach, & Gross-Tsur, 1995). Others emphasized low-level deficits and very basic deficiencies in processing magnitude information that may underlie DD (Ansari & Karmiloff-Smith, 2002). Such an approach leads to focusing on the building blocks of numerical cognition in order to characterize the performance of young adults suffering from DD.

Here, we report the results of three experiments. All three involved the processing of single-digit natural numbers (i.e., the numbers 1-9) that were shown to be numerical primitives (for a detailed discussion of this issue see Tzelgov et al., in press). In two of the experiments, we used the SiCE as a marker of automatic processing and in the third we used the SNARC effect. All experiments addressed the following question; to what extent does the automatic processing of numerical primitives by participants with dyscalculia differ from that of participants without dyscalculia? Experiment 1 focused on the modulation of the SiCE by intra-pair numerical distance and by the numerical size of the pairs physically compared.

Participant Sample Selection

Participants

A special effort was devoted to finding a sample that would allow testing the hypothesis of interest. Twenty-nine young adults participated in the study; 13 of them, who were previously diagnosed with dyscalculia, composed the clinical sample while the remaining 16 composed the control sample. Table 1 presents the characteristics of the clinical and control samples.

Selection Procedure

All participants but one were selected from the database of the Learning Disabilities Diagnostic Center at Achva Academic College. To increase the clinical sample, an additional participant was selected from the database of Orly Rubinsten's laboratory for learning disabilities at Haifa University. Both centers use MATAL (Ben-Simon & Inbar-Weiss, 2012) - a computer-based test battery for the diagnosis of learning disabilities (LD) in students in tertiary education. MATAL was developed by the national institute of testing and evaluation (henceforth, NITE) in cooperation with the Council of Higher Education in Israel (CHE) as part of an endeavor to develop a policy and procedure for standardizing and regulating the diagnosis of LD in higher education and thus facilitate the provision of test accommodations. MATAL assessment tools include 20 tests that assess the following skills: reading, writing, numeracy, attention, memory and visual perception. Of the 20 tests, three tests (seven performance measures) are used to diagnose numeracy functions: Computational Automaticity (retrieval of simple arithmetic facts), Procedural Knowledge (mastery of basic arithmetic procedures) and Number Sense (number-line representation). All MATAL tests were validated and normed (Ben-Simon & Inbar-Weiss, 2012).

A further selection of potential participants was carried out based on their performance on MATAL reading and attention tests. The inclusion criterion for all the participants was a score equal to or higher than the 10^{th} percentile. The inclusion criteria for the clinical sample was a performance score lower than the 20^{th} percentile on either one or both of the performance measures (RT and accuracy) of the Computational Automaticity and Procedural Knowledge tests.

It is important to note that in the clinical group, only two participants were also diagnosed with mild-moderate dyslexia and five of them were diagnosed with dysgraphia. None of the participants in either the clinical or the control groups had attention deficit hyperactivity disorder (ADHD).

Once the appropriate participants were identified for both the clinical group (N = 13) and the control group (N = 16), they were contacted and invited to participate in the study. All participants gave written consent to participate in the experiments and were rewarded with 50 NIS per hour for their participation. Each participant carried out all three experiments.

Experiment 1: Modulation of the SiCE by Numerical Size and Numerical Distance

This experiment focused on the distance effect and the size effect with the goal of testing to what extent controls differed from DD participants in their representation of the MNL. We used the SiCE as a marker of automaticity because it allowed probing the representation of the numbers 1-9 as mental primitives. Participants were presented in each trial with a pair of numbers differing in their numerical size and physical size, and they were required to judge which member of the pair was physically larger. If, as already mentioned, numbers are aligned along a mental number line and their numerical magnitude is automatically accessed, one should expect the SiCE to increase with the intra-pair numerical distance. Furthermore, if the representation along the MNL is compressed, one should expect that for a fixed intra-pair numerical distance, the SiCE should decrease with the magnitude of the numbers compared (e.g., it should be smaller for the pair (2 3) than for the pair (7 8)). From the perspective of the present study, the critical question was whether these modulations of the SiCE by the distance and the size effect would be further modulated by the difference between DD participants and controls.

Method

Stimuli and apparatus. The stimulus set was generated from Arabic numerals ranging from 1 to 9. There were four numerical distances: distance 1 (digit pairs: 1 2, 3 4, 6 7, 8 9); distance 2 (digit pair: 1 3, 2 4, 6 8, 7 9); distance 5 (digits pairs: 1 6, 2 7, 3 8, 4 9); and distance 6 (digit pairs: 1 7, 2-8, 3-9). Two sets of stimuli were generated—one for numerical size comparisons and the other for physical size comparisons. In the numerical comparison (NC) task, both digits in each of the pairs appeared in an equal physical size. The numbers were written in white Courier New font (size: 25 points) on a black background. Given that each pair appeared once with the numerically larger number on the left side and once with the numerically smaller number on the left side, this created a total of 30 pairs. Each pair appeared 8 times, giving a total of 240 randomly ordered trials for the NC task.

In the physical comparison (PC) task, the numerals in each pair appeared in two different physical sizes: large (Courier New font, size: 28 points) and small (Courier New font, size: 22 points). Each number pair appeared four times—equally in the congruent (e.g., 3 5) and incongruent (e.g., 3 5) condition, once with the physically larger number on the left side and once with the physically smaller number on the left side—creating a total of 60 trials. Each of these pairs appeared 4 times, giving a total of 240 randomly ordered trials for the PC task.

The experiment was conducted on an IBM personal computer with a 17-inch color screen monitor and was programmed in E-Prime software (Schneider, Eschman, & Zuccolotto, 2002).

Procedure

Each participant performed two kinds of comparisons (NC and PC) in separate blocks, with the PC block preceding the NC block. In the PC task, participants had to indicate which numeral in the pair was physically larger. In the NC task, participants were instructed to indicate which number in the pair was numerically larger. Participants were given a short rest break between the two tasks as well as after each sequence of 240 trials.

The experiment was conducted individually. Participants were seated about 60 cm from a computer screen. They were instructed to respond as quickly as possible, to avoid errors, to attend only to the relevant dimension, and to indicate which of two stimuli in a given display was numerically (numerical comparison) or physically (size comparison) larger. They indicated their choices by pressing one of two keys corresponding to the side of the display with the selected digit (i.e., "P" key for the right number or the “Q” key for the left one). A practice block of 12 trials followed the instructions. The experimental trials appeared in random order. Each trial started with a fixation cross that appeared at the center of the screen for 500 ms. Then a pair of digits were presented and remained in view until the participant pressed a key (but not for more than 3,000 ms). A new stimulus appeared 1,500 ms after the participant’s response. Each digit was 7.6 mm from the center of the screen. The inter-trial interval was 1,000 ms. There were 6 blocks in the physical task and 3 blocks in the numerical task.

Results and Discussion

To allow for testing the modulation of the SiCE by intra-pair numerical distance and by numerical size, we defined two binary factors. We defined pairs differing in numerical *size* as small when the mean numerical size of a pair was between 1.5 and 4.5 (e.g., for the pair (1 2) the size was 1.5; i.e., (1+2)/2) or as large when the mean numerical size of a pair was between 5.5 and 8.5. Similarly, numerical *distance* was defined as being short (between 1 and 2) or large (between 5 and 6). This resulted in a 2 (numerical size) x 2 (numerical distance) x 2 (congruency) x 2 (group: DD vs. control) factorial design with three within-participant factors and group as a between-participant factor. The dependent measure was RT. In all analyses the significance level was defined as $p < .05$.

A four-way analysis of variance (ANOVA) revealed that overall DD participants responded slower than controls did, $F_{(1, 23)} = 6.16$, $MSE = 62{,}738$, $\eta^2_p = .19$, and that their responses were slower for numerically larger pairs than for numerically smaller pairs,

$F_{(1, 26)} = 20.1$, $MSE = 332$, $\eta^2_p = .44$. In addition, their responses were faster in the congruent condition, $F_{(1, 26)} = 82.37$, $MSE = 1{,}660$, $\eta^2_p = .76$, which was further moderated by numerical distance, $F_{(1, 26)} = 25.9$, $MSE = 358$, $\eta^2_p = .50$. While the SiCE was significant in both distance conditions, $F_{(1, 26)} = 111.37$, $MSE = 975.5$, $\eta^2_p = .81$; $F_{(1, 26)} = 35.84$, $MSE = 1{,}042$, $\eta^2_p = .58$, for large and small distance, respectively, it was larger in the large distance condition, as indicated by the corresponding η^2_p measures and as presented in Figure 1. It is also important to emphasize that the relation between the SiCE and intra-pair distance was not moderated by group membership, $F < 1$, implying a negligible η^2_p, and in addition, the four-way interaction was not significant, $F_{(1, 26)} = 1.2$, *ns*, $\eta^2_p = .04$.

These results clearly show that the modulation of the SiCE by intra-pair numerical distance was very similar in DD and control participants.

Congruity was also modulated by numerical size, $F_{(1, 26)} = 25.9$, $MSE = 399$, $\eta^2_p = .67$. The SiCE was significant for both small, $F_{(1, 26)} = 88.35$, $MSE = 1{,}504$, $\eta^2_p = .77$, and large size pairs, $F_{(1, 26)} = 45.23$, $MSE = 554$, $\eta^2_p = .64$. It was larger in the small size condition as indicated by the relevant partial eta squared measures and as can be seen in Figure 2. This was not moderated by group membership as can be seen by the absence of both (already reported) a four-way interaction and a triple interaction of group x size x congruity, $F < 1$.

Thus we may conclude that the decrease of the size congruity effect with the increase of numerical size of numbers physically compared, characterizes the performance of DD and control participants alike.

Experiment 2: The Automatic End Effect

Goldman and Tzelgov (2014) replicated the end effect for the number 1 and showed that the number 9 does not serve as the upper end of the primitives. Experiment 2 compared the end effect and the AEE in DD and control participants.

Method

Stimuli. The stimuli were all pairs of numbers that could be generated using two different numbers from the set 1–9. In all trials the numbers were presented in Courier New font, in white color on a black background, and appeared on both sides (in different instances) of the center of the screen. In the *physical comparison task*, 36 physically congruent pairs were generated by presenting the number with higher numerical value in font size 28 and the number with lower numerical value in font size 22 (e.g., 2 8). The 36 physically incongruent pairs were created by presenting the number with the higher value in font size 22 and the number with the lower value in font size 28 (e.g., 2 8). In the *numerical comparison task* all numbers were presented in font size 28. In both tasks, each pair appeared 16 times in a counterbalance design with the larger number in half of the trials on the right side and in the other half on the left side.

There was a viewing distance of 57 cm between participants and the computer screen. The distance between the centers of the numbers was 5.5°. Numbers that appeared in font size 28 were 1.6° high and 1° wide. Numbers that appeared in font size 22 were 1.2° high and 0.8° wide.

Procedure

Participants performed the physical comparison task first followed by the numerical comparison task. In the physical comparison task, pairs of numbers varying in physical and numerical size were presented and participants were instructed to indicate which number was physically larger. In the numerical comparison task, pairs of numbers were of fixed physical size and participants were instructed to indicate which number had a larger numerical value. In both tasks, participants were instructed to press the L key if the chosen number was on the right and the A key if it was on the left. They were instructed to respond as quickly as possible while avoiding errors. Each task started with eight practice trials. The experimental trials appeared in random order. An experimenter was present during instructions and practice, making sure the task was understood. The pairs remained on the screen until the participant responded. Incorrect responses were followed by an error sound.

Results and Discussion

Analysis of response latencies was carried out for correct responses only (error rates were lower than 0.03). Extreme RT values (below 200 ms or above 1,000 ms) were excluded from the analysis (less than 0.04 of all trials). In all analyses the significance level was defined as $p < .05$.

Numerical task. Mean RTs of correct responses were first submitted to a two-way ANOVA with group (control vs. DD) as a between-participants variable and pair type (pairs containing 1, pairs containing 9, pair containing both 1 and 9, pairs containing neither 1 nor 9) as a within-participant variable. A main group effect was found, $F_{(1, 26)} = 19.67$, $MSE = 13{,}445$, $\eta^2_p = .43$, indicating that comparisons performed by the control group were faster (459 ms) than those by the DD group (557 ms). A main effect of pair type was also found, $F_{(3, 78)} = 161.72$, $MSE = 220$, $\eta^2_p = .86$ (see Figure 3).

The following set of comparisons was conducted separately for each group, as the interaction between group and pair type was significant, $F_{(3, 78)} = 11.52$, $MSE = 220$, $\eta^2_p = 30$. In the control group, RTs of comparisons of pairs containing 1 and both 1 and 9 were faster (436 ms) than comparisons of pairs containing 9 and neither 1 nor 9 (481 ms), $F_{(1, 26)} = 75.26$, $MSE = 435$, $\eta^2_p = .74$. These findings are consistent with the notion that in intentional numerical processing, 1 serves as the lower end of the set. Comparisons of the pair containing both 1 and 9 were faster (430 ms) than comparisons of pairs containing only 1 (442 ms), $F_{(1, 26)} = 8.17$, $MSE = 135$, $\eta^2_p = .24$, presumably due to a distance effect where the pair containing both 1 and 9 is the pair with the largest numerical distance. RTs for comparisons of pairs containing 9 (484 ms) and for pairs containing neither 9 nor 1 (478 ms) were similar, $F_{(1, 26)} = 3.12$, *ns*, indicating that 9 does not serve as the upper end in intentional numerical processing. A similar pattern of results was obtained for the comparisons performed by the DD group. Comparisons of pairs containing 1 and both 1 and 9 were faster (518 ms) than comparisons of pairs containing 9 and pairs containing neither 1 nor 9 (596 ms), $F_{(1, 26)} = 167.98$, $MSE = 435$, $\eta^2_p = .87$. This indicates that participants with DD intentionally processed 1 as the lower end of the set. Comparisons of the pair containing both 1 and 9 were faster (510 ms) than comparisons of pairs containing only 1 (525 ms), $F_{(1, 26)} = 10.40$, $MSE = 135$,

η^2_p = .29. RTs for comparisons of pairs containing 9 (595 ms) and of pairs containing neither 9 nor 1 (596 ms) were similar, $F < 1$, indicating that DD participants did not process 9 as the upper end of the set.

Numerical distance effects were examined in each group for each pair (see Figure 4). A significant linear trend indicating that RTs decreased with numerical distance was found for comparisons of pairs containing 1, $F_{(1, 26)}$ = 23.44, *MSE* = 756.24, η^2_p = .47, and was similar in both the control and DD group, $F < 1$. The linear trend effect for comparisons of pairs containing 9 was found for both the DD group, $F_{(1, 26)}$ = 132.64, *MSE* = 1,289, η^2_p = .84, and the control group, $F_{(1, 26)}$ = 67.58, *MSE* = 1,289, η^2_p = .72, though it was more pronounced in the DD group, $F_{(1, 26)}$ =11.05, *MSE* = 1,289, η^2_p = .30. The linear trend for comparisons of pairs containing neither 1 nor 9 was found for both the DD group, $F_{(1, 26)}$ =127.84, *MSE* = 619, η^2_p = .83,] and the control group, $F_{(1, 26)}$ = 79.04, *MSE* = 619, η^2_p = .75, and again was more pronounced in the DD group, $F_{(1, 26)}$ = 7.44, *MSE* = 619, η^2_p = .22. Note that the distance was larger for comparisons to 1, replicating the findings of Goldman and Tzelgov (2014).

Physical task. Mean RTs were submitted first to a 2 (group: control vs. DD) × 2 (physical congruency: congruent vs. incongruent) × 4 (pair type: pairs containing 1; 9; 1 and 9; and neither 1 nor 9) ANOVA. An SiCE was found as comparisons in the congruent size condition (469 ms) were faster than in the incongruent size condition (510 ms), $F_{(1, 26)}$ = 139.57, *MSE* = 656, η^2_p = .84. The effect of pair type was significant, $F_{(3, 78)}$ = 9.51, *MSE* = 156, η^2_p = .27, and moderated the SiCE, $F_{(3, 78)}$ = 41.79, *MSE* =203, η^2_p = .62, indicating that the SiCE varied with pair type (see Figure 5).

The triple interaction of pair type, congruency and group was not significant, $F < 1$, η^2_p = .01, nor was the interaction of pair type and group, $F_{(3, 78)}$ = 2.256, *ns*, η^2_p = .08, or the interaction of congruency and group, $F < 1$, η^2_p = .006. These result patterns indicate that the automatic numerical processing was similar for control and DD participants.

The next analyses were conducted together for the two groups: the SiCE was larger for comparisons of pairs containing 1 and pairs containing both 1 and 9 (465 ms in the congruent condition vs. 527 ms in the incongruent condition) compared with pairs containing 9 and pairs containing neither 1 nor 9 (480 ms in the congruent condition vs. 499 ms in the incongruent condition), $F_{(1,\ 26)}$ = 88.02, *MSE* = 275, η^2_p = .77, thus suggesting that 1 serves as the lower end in the set of primitives. The SiCE in pairs containing 9 (482 ms in the congruent condition vs. 498 ms in the incongruent condition) was smaller than the SiCE in pairs containing neither 1 nor 9 (477 ms in the congruent condition vs. 501 ms in the incongruent condition), $F_{(1, 26)}$ = 7.44, *MSE* = 64, η^2_p = .22, suggesting that 9 does not serve as the higher end of the primitives set. The size congruity effect for pairs containing 1 (467 ms in the congruent condition vs. 534 ms in the incongruent condition) was similar to the size congruity effect for pairs containing both 1 and 9 (464 ms in the congruent condition vs. 521 ms in the incongruent condition), $F_{(1, 26)}$ = 2.8, *ns*. This result implies that comparisons containing the lower end were determined mostly by the end stimulus and were relatively uninfluenced by the numerical distance.

The three types of pairs (pairs containing 1, pairs containing 9, and pairs containing neither 1 nor 9) were analyzed separately to test the linear trend of the interaction between the intra-pair distance and the size congruency effect (see Figure 6).

For all pair types, the interaction between the intra-pair distance and the SiCE was similar for both groups, $F < 1$, therefore for each pair type, data of the two groups was analyzed together. In comparisons of pairs containing 9, the SiCE increased with larger numerical distance, $F_{(1, 26)}$ = 34.47, *MSE* = 583, η^2_p = .57. Similarly, in comparisons of pairs containing neither 1 nor 9, the SiCE increased with larger numerical distance, $F_{(1, 26)}$ = 21.92, *MSE* = 180, η^2_p = .46. There was no linear moderation of numerical distance on the SiCE in pairs containing 1, $F_{(1, 26)}$ = 1.93, *ns*.

To conclude, the obtained AEE (increased SiCE that is insensitive to intra-pair distance) for comparisons including 1 validated the claim that 1 (but not 9) serves as an end stimulus. Furthermore, the AEE characterized performance in DD participants and controls alike.

Experiment 3: The SNARC Effect

As already mentioned, the SNARC effect is another way to show access to the MNL. Until recently, there was no evidence of the SNARC effect in Hebrew readers but now Zohar-Shai et al. (2014) have shown that one method to obtain the effect in Hebrew is to run the two mapping conditions on different days. We applied this method in the present study.

Method

Stimuli and apparatus. The stimuli were single Arabic digits ranging from 1 to 9 (5 excluded), presented one at a time at the center of a screen and written in Times New Roman font (size: 32 points) in white color on a black background. Within a single block, each number appeared eight times in random order, resulting in a block of 64 randomly ordered trials. Each experimental block was preceded by 10 training trials, which were not analyzed.

The experiment was conducted on an IBM-PC with stimuli presented on a 17-inch monitor screen from a viewing distance of approximately 50 cm. E-Prime software controlled the presentation of stimuli. Responses were given on a standard QWERTY keyboard.

Procedure

The task was to make a speeded parity judgment for each digit. The participant had to respond with the pointing finger of one hand if the digit was an even number and with the pointing finger of the other hand if it was an odd number. The "Q" key was used for the left-hand key response and the "P" key was used for right-hand key response. Participants were asked to respond as quickly as possible but to avoid errors. Speed and accuracy of each response were recorded.

Each trial started with a fixation cross that appeared at the center of the screen for 200 ms, followed by a blank screen for 300 ms, and then the number stimulus appeared and remained visible until the participant responded or 3,000 ms elapsed. After response, there was a 1,300 ms interval of a blank screen before the next trial started.

The participants were told that they would see numbers between 1 and 9. They were to decide whether each number was odd or even by pressing one of two response keys. The instructions emphasized both speed and accuracy. Half of the participants were instructed to respond in the first block with the right hand to odd numbers and with the left hand to even numbers. This mapping was reversed for the second half of the participants. Each participant performed the task again a week later with the opposite parity-to-hand mapping.

Results and Discussion

The trials with incorrect responses (2.68%) and RTs longer or shorter than two standard deviations from the mean (5.55%) were removed from further analysis. Median RTs for correct responses were computed for each participant, each side of response, and each target.

The data was analyzed in a 2 (response side: left vs. right) x 4 (magnitude: 1.5, 3.5, 6.5, 8.5) x 2 (parity) factorial design with three within-participant factors and group (DD vs. control) as a between-participants variable.

The ANOVA revealed a significant group effect, $F_{(1, 26)} = 26.50$, $MSE = 173{,}594$, $\eta^2_p = .50$, indicating that the responses of the control group were 204 ms faster than those of the DD group (498 ms vs. 702 ms, respectively). Participants responded faster (589 ms vs. 611 ms) with the right-hand key than with the left-hand key, $F_{(1, 26)} = 6.35$, $MSE = 8{,}879$, $\eta^2_p = .20$. The interaction between number magnitude and parity was significant, $F_{(3, 78)} = 6.74$, $MSE = 6{,}015$, $\eta^2_p = .20$, and was also modulated by group, $F_{(3, 78)} = 4.12$, $MSE = 6{,}015$, $\eta^2_p = .14$. This interaction indicated that as number magnitude increased, the responses to even numbers became faster while the responses to odd numbers became slower. This interaction was significant for the DD group, $F_{(1, 26)} = 16.54$, $MSE = 7{,}785$, $\eta^2_p = .39$, but not for the control group, $F_{(1, 26)} = 1.09$, $MSE = 7{,}785$, $\eta^2_p = .04$. Most importantly, the interaction between side of response and number magnitude was significant, $F_{(3, 78)} = 14.87$, $MSE = 2{,}351$, $\eta^2_p = .36$, as was the linear contrast for this interaction, $F_{(1, 26)} = 26.07$, $MSE = 3{,}759$, $\eta^2_p = .50$. The mean linear regression slope was -11.02. Note that in the present report, we analyzed linear effects within the framework of a repeated-measures ANOVA as suggested by Pinhas, Tzelgov, and Ganor-Stern (2012). Also note that the statistical testing of each (simple) linear trend interaction between side of response and number magnitude checks if the RT difference between the right-hand key response and the left-hand key response (dRT) significantly decreases as the number magnitude increases (for further discussion of testing linear effects in an ANOVA, see Pinhas et al., 2012).

This interaction was not moderated by group as can be seen by the absence of a triple interaction of response side x number magnitude x group, $F_{(3, 78)}$ = 1.73, *MSE* = 2,351, η^2_p = .06. There were no other significant effects.

The interaction between response side and number magnitude was calculated separately for each group. For the DD group, interaction between the side of response and number magnitude was significant, $F_{(3, 36)}$ = 8.21, *MSE* = 3,498, η^2_p = .40, as was the linear contrast for this interaction, $F_{(1, 13)}$ = 13.13, *MSE* = 6,323, η^2_p = .52. The mean linear regression slope was -14.84 (see Figure 7).

For the control group, the interaction between the side of response and number magnitude was significant, $F_{(3, 42)}$ = 6.48, *MSE* = 1,368, η^2_p = .32, as was the linear contrast for this interaction, $F_{(1, 14)}$ = 14.39, *MSE* = 1,562, η^2_p = .50. The mean linear regression slope was -7.19 (see Figure 8).

Conclusions and Implications

In this study we investigated the internal representation of single-digit natural numbers by young adults with developmental dyscalculia and healthy controls. The participants in the DD group were characterized by minimal comorbidity; none of the 13 of them was diagnosed with ADHD, two were diagnosed with mild dyslexia and five with mild dysgraphia. We assumed that we tapped into the semantic representation minimally affected by intentional strategies because we evaluated automatic processing of numerical magnitude under conditions in which such processing was not part of the task requirements.

We employed two markers of automatic processing of numerical information; the SNARC effect that allows testing whether numbers are represented along a mental number line, and the SiCE that allows testing different features of such a representation. To estimate the SNARC effect, participants performed a parity decision, while to estimate the SICE, they performed physical size comparisons of the numerals presented.

The effects reported characterized both groups alike (no effect of interest was moderated by group membership) and were significant and of impressive magnitude in each group:

- There was a SNARC effect indicated by a negative correlation between the difference between the two hands in the parity task and the number magnitude. Such a finding supports the hypothesis that the MNL spreads from left to right.
- The SiCE increased with the intra-pair numerical distance, consistent with the notion that numbers are arranged along the MNL according to increasing numerical magnitude.
- The SiCE decreased with the average (numerical) magnitude of the numbers compared, consistent with the hypothesis of a compressed representation.
- The emergence of the arrangement of numbers along the MNL is apparently contributed to not just by a comparison process but also by the mapping of 1 as an end stimulus (the smallest number).

What is particularly important is the commonality of these finding in the two groups. The only difference between the two groups we can point to in regard to numerical processing is the processing speed of numerical information—the members of the control group were much faster. However, participants with DD did not differ from the controls in their mental representation of numbers. Both groups showed similar SNARC and SiCE effects. In each of the groups, the SiCE was moderated to the same extent by the same factors—the intra-pair distance and the (average) magnitude of the numbers presented. Furthermore, in both groups the number 1 showed an automatic end effect (for a detailed discussion of the end effect see (Pinhas & Tzelgov, 2012)). Thus we may conclude that as far as the mental representation of the natural numbers 1-9 is of interest, young adults with DD did not differ from controls.

When interpreting these results one should keep in mind that the DD group in our study was characterized by minimal comorbidity. Rubinsten and Henik (2009) made the distinction between developmental dyscalculia (DD) as a deficit in core numerical abilities and the more general concept of mathematical learning disabilities (MLD). According to their analysis, the defining features of DD are a deficit in the IPS and minimal comorbidity. Given the minimal comorbidity of our participants, one possibility is that they belong to this category. Assuming this to be true, the present study allows concluding that at least for our young adults with DD, the impairment is not caused by deficiencies in the mental representation of single-digit natural numbers, which are the building blocks of the symbolic representation of quantities (Tzelgov et al., in press). Yet, it may be that the deficient performance of the DD participants in our study reflects a deficiency in non-symbolic numerical representation. That is, the fact that no differences were found in the current study between performance of DD participants and controls when using symbolic numbers as stimuli, may suggest that the symbolic mental number line is not deficient in those with DD but rather their processing of non-symbolic stimuli is. Specifically, numerical representations are thought to rest on two distinct representation systems; symbolic (as has been investigated in the current study) and non-symbolic. The non-symbolic representation (e.g., group of dots; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 2005) develops without formal teaching and is commonly attributed to an analog, approximate system.

While most of the studies favor a strong overlap between symbolic and non-symbolic number representation systems in adults (e.g., Furman & Rubinsten, 2012; Nieder & Dehaene, 2009; Piazza, et al., 2010; Santens, Roggeman, Fias, & Verguts, 2010), recently Lyons, Ansari, and Beilock, (2012) argued that in adults, a digit and its corresponding quantity (e.g., array of seven dots and the digit '7') are not related (see also Sasanguie, Defever, Maertens, & Reynvoet, 2014). Hence, it could be that supporting the current finding, the symbolic mental number line is not deficient in those with DD but rather the non-symbolic representation is. Indeed, even when using a symbolic comparison task (as was done in the current study), deficits in basic magnitude representation or quantity processing may appear. For example, Soltész and colleagues (Soltész, Szűcs, Dékány, Márkus, & Csépe, 2007) found that adolescents with DD show no late event-related brain potentials (ERPs) distance effect between 400 ms and 440 ms on right parietal electrodes when comparing Arabic numerals. Such a finding may indicate that the processing of the magnitudes of numerical information is abnormal in those with DD. Accordingly, to a certain degree, our finding then, supports previous ones.

Current findings show no differences between DD participants and controls in numerical symbolic representations and hence, suggest a deficit in the non-symbolic numerical system, which is separately represented. The question then is, how we found initial differences in our symbolic assessment tasks included in MATAL that differentiated between the DD and control groups. To answer this question it is important to note that many studies have demonstrated a positive correlation between non-symbolic numerical representations and symbolic mathematical proficiency (e.g., Bonny & Lourenco, 2013; Halberda, Mazzocco, & Feigenon, 2008; Inglis, Attridge, Batchelor, & Gilmore, 2011; Libertus, Feigenson, & Halberda, 2013). For example, previous studies have shown that more skillful estimators tend to have better conceptual understanding of mathematics (LeFevre, Greenham, & Naheed, 1993), better counting and arithmetic skills (LeFevre et al., 1993) and higher math achievement test scores (Siegler & Booth, 2004). The non-symbolic numerical system has been shown to be correlated with processing mathematical information in adults (Lourenco, Bonny, Fernandez, & Rao, 2012). In addition, participants who suffer from DD were found to have a lower acuity of non-symbolic representation that was similar to the acuity of children who were five years younger (Piazza et al., 2010). Alongside correlation studies, longitudinal studies have shown that non-symbolic numerical estimation skill during kindergarten is correlated with a better (symbolic) mathematics ability six months later (Libertus et al., 2013). It should be emphasized however, that our hypothesis that non-symbolic numerical representation and not symbolic representation is deficient in cases of DD, requires further research.

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Table 1 - Characteristics of the Clinical and Control Samples

Sample	N	Gender		Age (yrs.)		
		Male	Female	Range	Mean	SD
Clinical	13	4	9	22-28	24.6	2.17
Control	16	13	3	23-28	25.5	1.63

Figure 1 - Mean RTs in Experiment 1 as a function of congruency, numerical distance and group

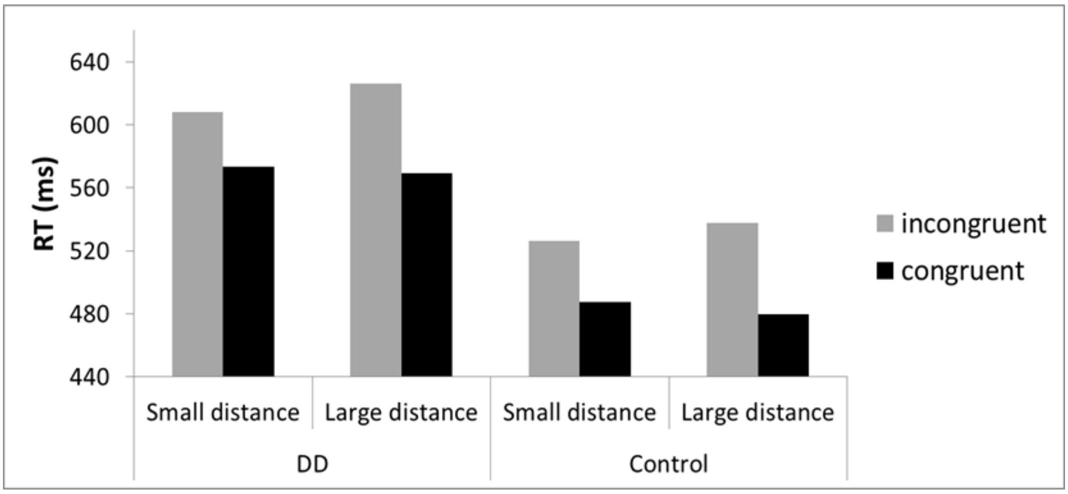

Figure 2 - Mean RTs in Experiment 2 as a function of congruency, size and group

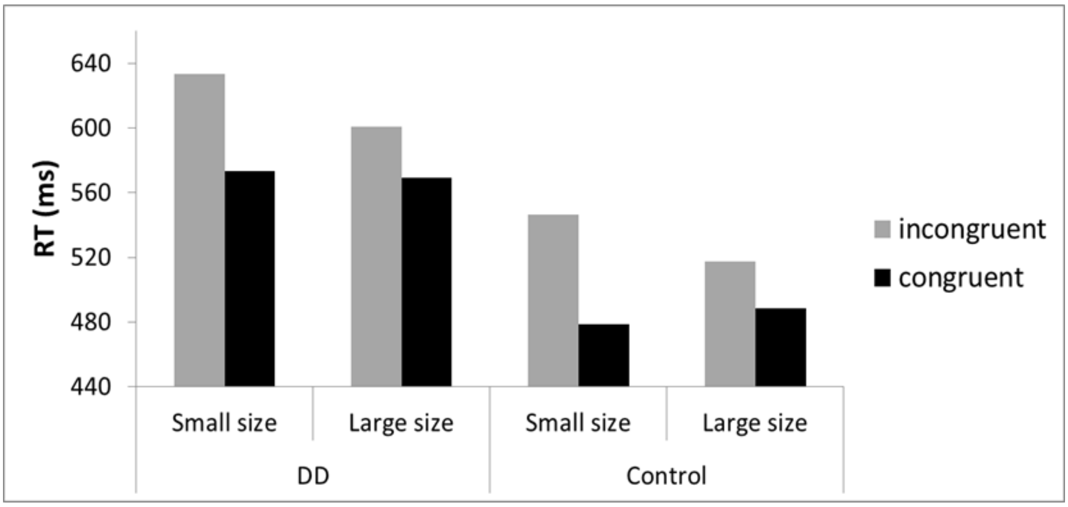

Figure 3 - RTs for the numerical comparison task in Experiment 2 as a function of group and pair type.

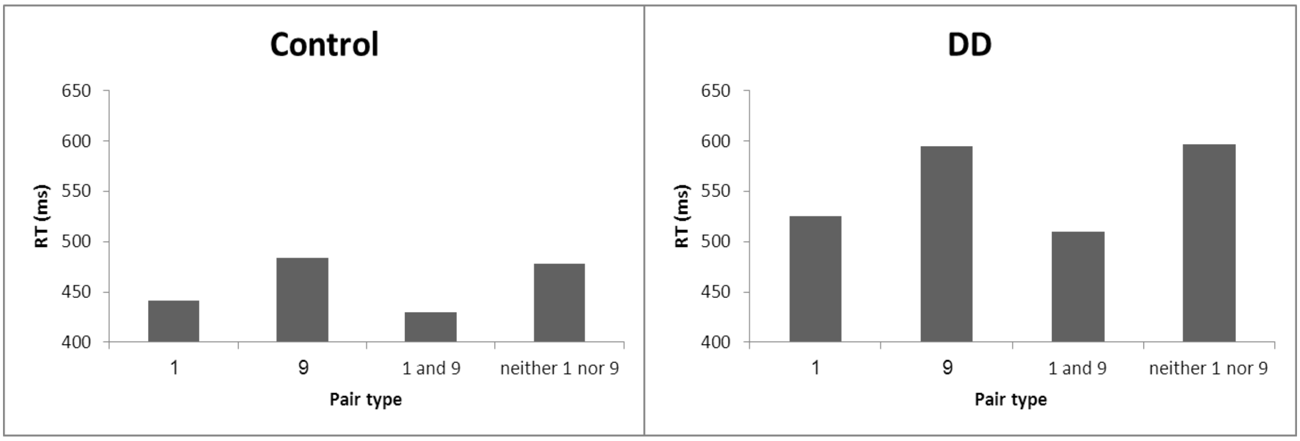

Figure 4 - RTs for the numerical comparison task in Experiment 2 by group, pair type and numerical distance.

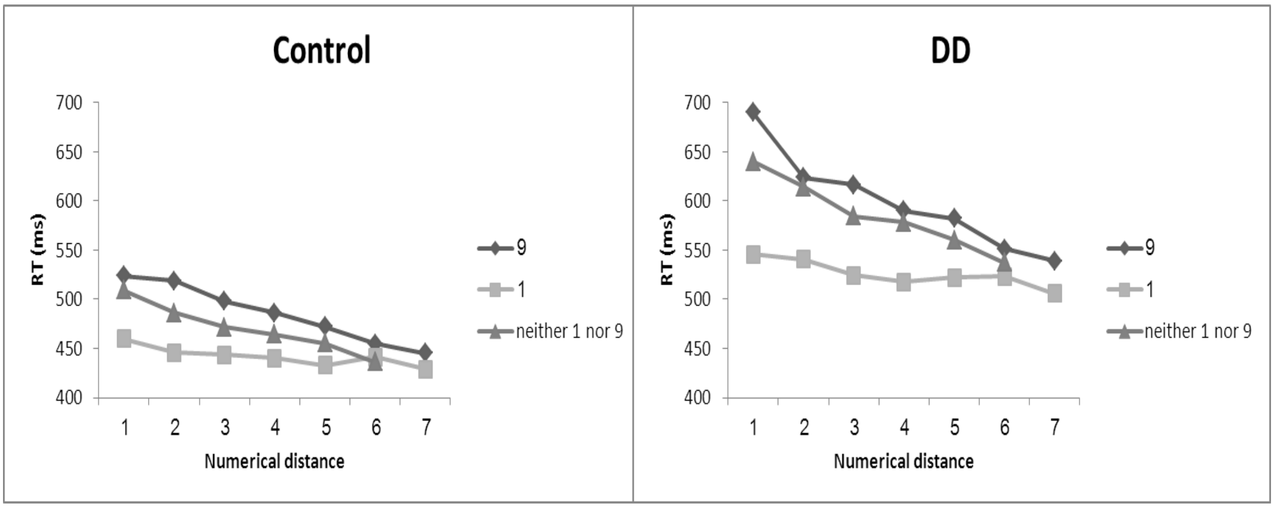

Figure 5 - RTs for the physical comparison task in Experiment 2 as a function of group, congruency and pair type.

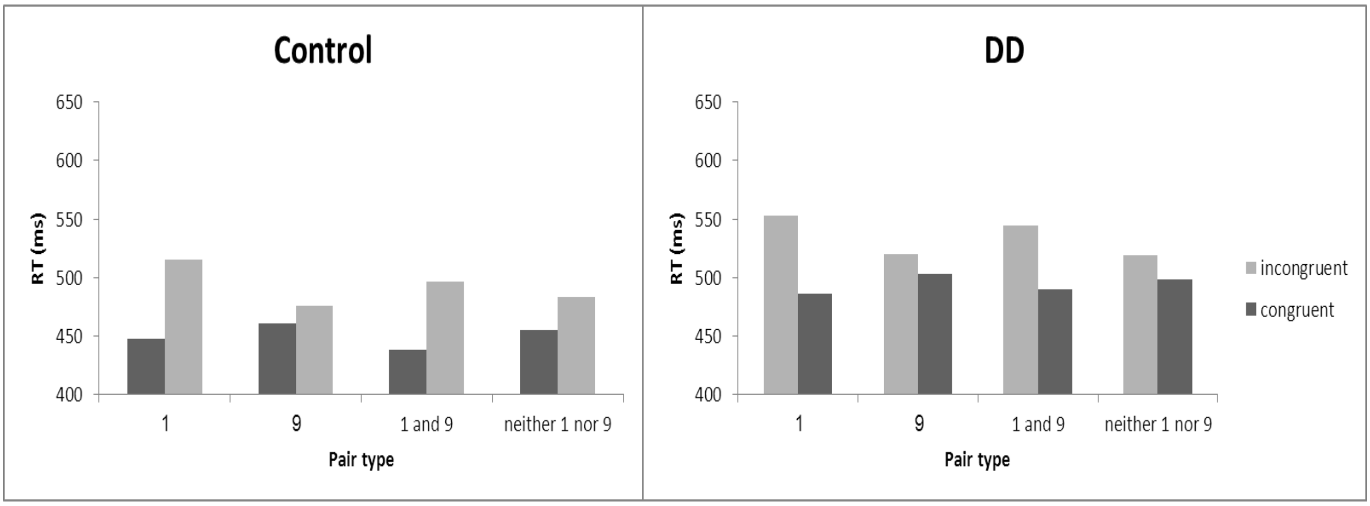

Figure 6 - RTs for the physical comparison task in Experiment 3 as a function of group, congruency, pair type and numerical distance.

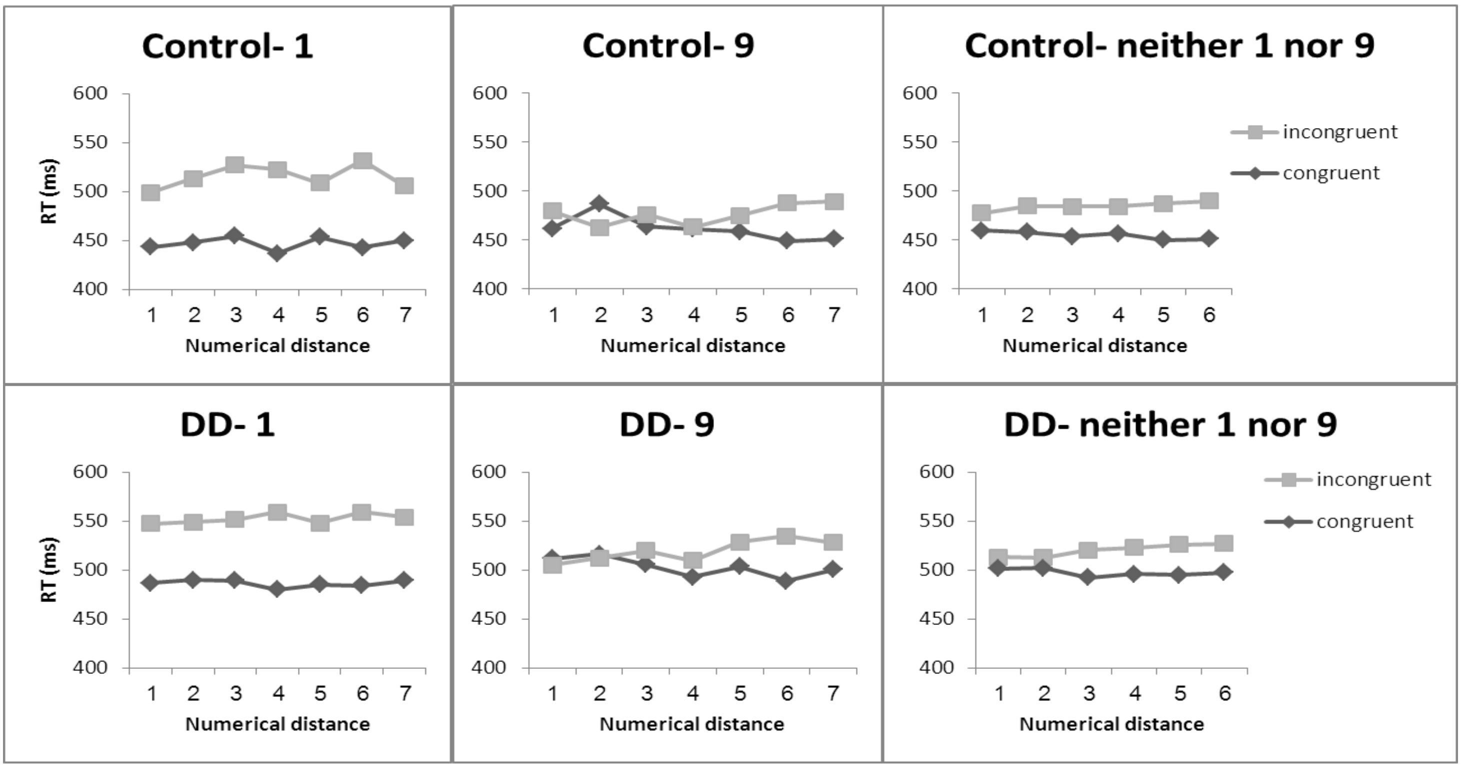

Figure 7 - The SNARC effect in the DD group

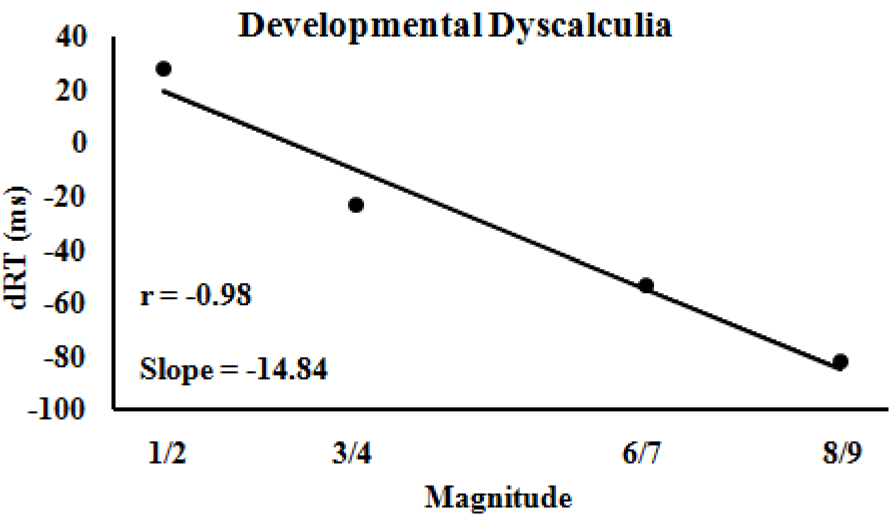

Figure 8 - The SNARC effect in the control group