Does Attentional Training Improve Numerical Processing in Developmental Dyscalculia?

Sarit Ashkenazi and Avishai Henik
Ben-Gurion University of the Negev

Objective: Recently, a deficit in attention was found in those with pure developmental dyscalculia (DD). Accordingly, the present study aimed to examine the influence of attentional training on attention abilities, basic numerical abilities, and arithmetic in participants who were diagnosed as having DD. Method: Nine university students diagnosed as having DD (IQ and reading abilities in the normal range and no indication of attention-deficit hyperactivity disorder) and nine matched controls participated in attentional training (i.e., video game training). Results: First, training modulated the orienting system; after training, the size of the validity effect (i.e., effect of valid vs. invalid) decreased. This effect was comparable in the two groups. Training modulated abnormalities in the attention systems of those with DD, that is, it reduced their enlarged congruity effect (i.e., faster responding when flanking arrows pointed to the same location as a center arrow). Second, in relation to the enumeration task, training reduced the reaction time of the DD group in the subitizing range but did not change their smaller-than-normal subitizing range. Finally, training improved performance in addition problems in both the DD and control groups. Conclusions: These results imply that attentional training does improve most of the attentional deficits of those with DD. In contrast, training did not improve the abnormalities of the DD group in arithmetic or basic numerical processing. Thus, in contrast to the domain-general hypothesis, the deficits in attention among those with DD and the deficits in numerical processing appear to originate from different sources.

Keywords: attention, training, developmental dyscalculia

Developmental dyscalculia (DD) is a disorder in mathematical abilities presumed to be attributable to a specific impairment in brain function (von Aster & Shalev, 2007; Wilson & Dehaene, 2007). Typically, DD is considered to be a unique deficit not caused by a reading disorder (dyslexia), attention disorder (attention-deficit hyperactivity disorder (ADHD)/attention deficit disorder), or general intelligence problems.

Recently, we found that along with the deficits in numerical processing, those with DD have deficits in attention. Specifically, they presented deficits in line bisection, selective/executive attention, and alertness (Ashkenazi & Henik, 2010a, 2010b). In the present work we will examine the influence of attentional training on attention and numerical processing in those with DD.

Characteristics of DD

Children with DD fail in a wide range of numerical tasks. For example, they present difficulties in retrieval of arithmetical facts (Geary, 1993; Ginsburg, 1997; Russell & Ginsburg, 1984; Shalev & Gross-Tsur, 2001), in using arithmetical procedures (e.g., Russell & Ginsburg, 1984), and in solving arithmetical operations in general (Geary, Hamson, & Hoard, 2000).

Recently, studies of DD have concentrated on basic numerical processing and have indicated difficulties in several processes: magnitudes comparison (Ashkenazi, Mark-Zigdon, & Henik, 2009; Geary, Hamson, & Hoard, 2000; Rubinstein & Henik, 2005, 2006) and enumeration (Geary, Bow-Thomson, & Yao, 1992; Geary, Hamson, & Hoard, 1999; Koontz & Berch, 1996; Landerl, Bevan, Butterworth, 2004). Because we used enumeration in the current study, we present this task in more detail. Enumeration involves two processes: subitizing, defined as a fast and accurate assessment of a number of small quantities (Kaufman, Lord, Reese, & Volkman, 1949), and counting, used for large arrays of stimuli. It is accepted that the subitizing range is between one to four items (e.g., dots). Children with arithmetical learning disabilities showed a smaller subitizing range or slower responding within the subitizing range (Ashkenazi, Mark-Zigdon, & Henik, 2010; Koontz & Berch, 1996; Van der Sluis De Jong, & van der Leij, 2004). In addition, a smaller subitizing range was observed in those with arithmetical learning disabilities of genetic origin (e.g., Turner syndrome—TS; Bruandet, Molko, Cohen, & Dehaene, 2004) and acquired arithmetical disabilities (Ashkenazi, Henik, Ifergane, & Shelef, 2008; Delazer, Karner, Zamarain, Donnemiller, & Benke, 2006).
Note, however, that difficulties in mathematics tend to be heterogeneous with a high rate of comorbidity (many children have both dyslexia or attention deficit/hyperactivity disorder and dyscalculia) and multiple diagnostic criteria (see Rubinsten & Henik, 2009, for review). The next section will address this issue.

Does DD Involve Domain-General or Domain-Specific Deficits?

It has been suggested that the deficit in DD involves the intraparietal sulcus (IPS) (Cohen Kadosh et al., 2007; Isaacs, Edmonds, Lucas, & Gadian, 2001; Molko et al., 2003; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007). Accordingly, one line of thinking is that DD is a domain-specific (pure) disorder that involves only deficits in basic numerical processing and is related to one biological marker (i.e., a deficit in the IPS; see Rubinsten & Henik, 2009). Alternatively, some refer to deficits in arithmetic as a domain-general phenomenon (e.g., Rotzer et al., 2008). In addition, one of the main deficits in DD is a difficulty in retrieval of arithmetical facts (e.g., Kaufmann, Loch, Drexler, & Semenza, 2004; Temple, 1991; Wilson & Dehaene, 2007). It has been suggested that this difficulty is more related to deficits in attention, working memory, or long-term memory than to deficits in conceptual knowledge of arithmetic (e.g., Geary, 2004). Furthermore, there are indications that mathematical abilities are directly related to general abilities such as executive functions (e.g., Bull & Scerif, 2001) and verbal or visuospatial working memory (e.g., Wilson & Swanson, 2001). Last, Karmiloff-Smith (2006) suggested that developmental disorders characterized by a domain-specific end state can stem from a domain-general starting point.

In line with this view, we recently found that even those with “pure” DD present deficits in attention (Ashkenazi & Henik, 2010a, 2010b). The attentional deficits found were not identical to the deficits presented in ADHD.

Attention and DD

Recently, Ashkenazi and Henik (2010a) examined the three attentional networks of alerting, orienting, and executive control (Fan, Fossella, Sommer, Wu, & Posner, 2003; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Fan, Wu, Fossella, & Posner, 2001; Fossella, Posner, Fan, Swanson, & Pfaff, 2002; Posner & Petersen, 1990) among those with DD using the ANT-I (Attention Networks Test and Interactions) task (created by Callejas, Lupianez, & Tudela, 2004) and discovered deficits in the alerting (larger alerting effect) and the executive function network (larger congruity effect, see below) among those with DD. Moreover, they revealed a deficit in visual attention among DD participants (Ashkenazi & Henik, 2010b). Visuospatial attention is needed in solving multi-digit equations, enumerating groups of objects, comparing quantities according to magnitude, and in writing equations (e.g., borrowing).

As mentioned earlier, those with DD presented deficits in basic numerical processing; some of these deficits could be connected to deficits in attention. This has been shown for subitizing (Railo, Kiovisto, Revonsuo, & Hannula, 2008) and for the numerical Stroop task (Ashkenazi, Rubinsten, & Henik, 2009). Moreover, it has been shown that subitizing might be affected by training with video games (Green & Bavelier, 2003). In addition, recently Rotzer et al. (2009) examined visual working memory abilities in children diagnosed as having DD using fMRI and behavioral measurements. Importantly, impaired brain activity was found during the spatial working memory task: 1) reduced activation was found in the right IPS, right insula, and the right inferior frontal lobe, and 2) the level of activity in the right IPS was positively correlated with the accuracy rate in a spatial working memory task. Note that attention modulates visual working memory by changing the relation between the target and distractors (for more details regarding the connections between working memory and attention, see Downing, 2000). Accordingly, difficulties in attention could be related to difficulties in visual working memory among those with DD. The results of this study may imply that the attentional deficits and the numerical deficits in DD are closely related.

Attentional Training Using Video Games

Green and Bavelier (2003) suggested that intensive training in video games can improve attention abilities. Video game players seemed to have improved executive functioning as indicated by the flanker task. In addition, playing video games enlarged the subitizing range (up to 4.9 items). These results were obtained both in groups of “natural” video game players and in naive participants who were experimentally trained in video games. The authors suggested that training with 3D action video games could improve visual attention and executive function abilities. In contrast, Castel, Pratt, and Drummond (2005) examined orienting of attention and visual search and reported that players and nonplayers showed similar attention effects and differed only in speed of responding. Recently, Dye, Green and Bavelier (2009) examined the difference between video game players and non video game players in the ANT test. This test examined the three attentional networks described above. The results indicated a larger flanker effect and smaller orienting effect among video game players compared with non video game players. Additional studies (e.g., De Lisi & Wolford, 2002) with different video games (e.g., Tetris) reported improvement in visuospatial abilities after video training. There are indications that the use of specific computerized attention training can improve executive function abilities (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005), as well as working memory and mathematics in low working memory groups (Holmes, Gathercole, & Dunning, 2009). Moreover, noncomputerized attention training was found to improve the accuracy of arithmetical problems in children who were diagnosed with ADHD (Kerns, Eso, & Thomson, 1999).

The Present Study

As mentioned earlier, the assumption that DD is a solitary domain-specific disorder was in doubt (Ashkenazi & Henik, 2010a, 2010b). The current study was designed to examine whether DD is a domain-specific or domain-general disorder, by investigating the effects of video game training in those with DD. Previous studies showed that video game training improved attention (especially the visual and executive function networks) (e.g., Castel et al., 2005; Dye et al., 2009; Green & Bavelier, 2003). Moreover, it seems more likely that students will have higher motivation to play 3D action video games compared with traditional attention training games. Because of these facts, we used a
video game named “Call of Duty” (similar to the one that was used by Green & Bavelier, 2003) to train college students suffering from DD. After 10 days of training we tested the DD and the control groups in attention and numerical functioning. Attention was tested using the ANT-I, while basic numerical processing was examined by an enumeration task, and arithmetic was examined by several computerized tests.

If attention is at the heart of the DD deficiency, attention training would improve not only attentional performance (i.e., performance in the ANT-I test) but also numerical processing. This would fit with the domain-general hypothesis. In contrast, if the attentional deficiency in DD is not necessarily related to the numerical deficiency, attention training may show a specific attentional effect. Namely, it would influence performance in the ANT-I but not in numerical tests. This would suggest that numerical and attentional deficiencies, presented by those with DD, are independent. Needless to say, if video game training improves performance in general but does not affect DD deficiencies, its effect will be comparable in the two groups (DD and control). Specifically, we hypothesize that attention training will generally improve the subitizing range of the control group. In relation to the DD group, an increase in the abnormal subitizing range of the DD participants will indicate that the basis of this deficit is related to deficits in attention. In relation to arithmetic, it has been suggested that numerical calculation involves the use of working memory (i.e., keeping information available in the cognitive system) and attention (Rubenstein & Henik, 2009). However, the involvement of attention and working memory is more related to addition (that involves direct retrieval from memory) than to subtraction (that involves the semantic code of numbers) (Dehaene & Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003). Accordingly, we hypothesize that addition operations will benefit more from the training compared with subtraction operations. As in the case of subitizing, a lack of group differences after the attention training will suggest that attention is involved in arithmetic in general but not specifically in the difficulties that characterize DD.

Method

Participants

Eighteen students from Ben-Gurion University of the Negev and Achva Academic College participated in the experiment. Nine of them were diagnosed as suffering from DD, and the other nine were age- and sex-matched controls. The controls did not have any learning or other disabilities. None of the participants in the two groups played video games pervious to experiments and did not receive previous intervention for difficulties in mathematical abilities. All students were paid 700 NIS ($175) for participation in the experiment or were awarded a course credit.

DD group. The DD group was composed of nine subjects, seven of them were females, with a mean age of 24.7 years ($SD = 1.98$). All the participants in the group were diagnosed as having DD according to Rubinstein and Henik’s (2005, 2006) criteria. Before the beginning of the experiment, every candidate was tested individually for DD, dyslexia, IQ, and ADHD. All of the participants were college students that volunteered for the experiment because of severe difficulties in numerical processing. They had no indication of deficits in reading or attention. Approximately 50 participants who met these criteria volunteered for the experiment. Out of these 50, 30 passed the interview stage and underwent a full diagnosis. Eighteen participants met the DD criteria. Four were excluded from this DD sample; two because of being diagnosed as suffering from ADHD and two because of relatively low IQ. After the first day of training, two DD participants and two controls were not willing to continue because of the characteristics of the game. Another three DD were excluded because of the fact that they frequently played video games before the experiment. That left us with nine participants defined as having pure DD.

For diagnostic tools see Ashkenazi and Henik (2010a). Briefly, the mathematical ability test was administered individually. Time was measured for every subtest and was divided by the number of trials in the subtest (when applicable) to give an average RT. The test was divided into two parts, the first part dealing with number comprehension and production, and the second part dealing with calculation.

Part 1 - Number comprehension and production. The subtests in Part 1 were as follows:

1. Comparing digits. Participants were asked to insert the appropriate expression between two numbers: smaller than (<), larger than (>) or equal (=).
2. Counting forward and backward between two numbers.
3. Estimation of quantity. The participants had to estimate, but not calculate exactly, the result of an operation between two numbers.
4. Series progression (non-numerical).
5. Numerical series. The participants had to complete arithmetical series (e.g., 20, 40, 60, _____).
6. Comparing fractions. The participants had to compare pairs of fractions and decimals and select <, > or =.
7. Verbal problems. Participants were asked to 1) Circle the correct operation for the given problem (e.g., addition,), 2) Write down the equation, 3) Solve the equation.

Part 2 – Calculation. There were six subtests in Part 2 as follows:

1. Simple pure operations. Single-digit operations were administered.
2. Simple mixed operations. Single-digit operations were administered, mixed in one block in a random order.
3. Horizontal operations. For example, $554 + 96 = .$
4. Vertical operations. Two- or three-digit numbers were presented in a vertical alignment, with an indicated operation.
5. Decimals. Decimal equations were administered, for example, $0.5 + 0.96 = .$
6. Fractions. Fraction equations were administered, for example, $1/4 + 1/2 = .$ (See Table 1 and 2 for more details.)
We used a reading test that was composed and published by Shalev and colleagues (Shalev, Manor, Amir, & Gross-Tsur, 1993) and standardized in a separate study (Shalev & Gross-Tsur, 2001). The full tasks of this assessment can be seen in Rubinsten and Henik (2005). Our sample of DD students did not have any reading difficulties, and there were no differences in the scores of any reading tests between them and the control group. We converted the scores.

For examination of attention deficits we used the Conners’ Continuous Performance Test II (CPT II V.5) (see Ashkenazi & Henik, 2010a). We excluded two participants from the DD group because of deficits in attention difficulties in the CPT and in the questionnaire. There were no significant differences in attention abilities between the DD and the control group. Probability of ADHD was 27% for the DD and 28% for the control group, F < 1. In addition, there was no significant difference between the control and the DD groups in the omission, F < 1, or commission error rates. ns. See Table 3 for the reading and attention measurements of the two groups.

**Control group.** The control group included nine participants, of which seven were females, with a mean age 23.5 years (SD = 1.2). All of them were age and sex matched to the DD group. No participant in this group was diagnosed as having DD or any other learning disability in the past. All of them took the arithmetic, reading, Raven’s Progressive Matrices, and CPT II tests and did not show any current learning disability.

### Experimental Tasks

**Subitizing and counting.** In each trial, participants were presented with a group of dots at the center of a screen. Participants were asked to say aloud the number of dots that were presented as quickly as possible without making mistakes. The arrangement of dots was either random or canonical (i.e., similar to the arrangement on a playing cube).

The number of dots varied between 1 and 9. Vocal RTs and errors were recorded. The events in a typical trial were as follows:

<table>
<thead>
<tr>
<th>Simple pure operations (RT)</th>
<th>Control</th>
<th>DD</th>
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<tbody>
<tr>
<td>12%</td>
<td>29%</td>
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<td>20%</td>
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<td>9%</td>
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<tr>
<th>Vertical operations (RT)</th>
<th>Control</th>
<th>DD</th>
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<tbody>
<tr>
<td>8%</td>
<td>13%</td>
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<tr>
<td>25%</td>
<td>40%</td>
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<td>29%</td>
<td>41%</td>
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<tr>
<th>Decimals (RT)</th>
<th>Control</th>
<th>DD</th>
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<td>27%</td>
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<td>30%</td>
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<tr>
<th>Fractions (RT)</th>
<th>Control</th>
<th>DD</th>
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<td>8%</td>
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<td>5%</td>
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<td>9%</td>
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Note. Mean RT is in milliseconds and error rates in percentage. An asterisk indicates a significant difference between the performance of the DD group and the control group.

*p < .05. **p < .01.
trials over two blocks: 2 arrangements (canonical, random) × 9 quantities × 8 repetitions × 2 blocks.

ANT-I. The ANT-I was administered according to Callejas et al. (2004). Briefly, the procedure is a combined cuing and flanker task. In each trial a line of five arrows was presented in the middle of the screen. The participants were instructed to attend to the middle arrow and to decide whether it was pointing to the left or to the right frequency tone. The participants had to press a left hand-key if the central arrow was pointing left and a right hand-key if it pointed right.

Arithmetic tasks. There were five arithmetic tests:

Before the beginning of every test, three or four training trials were given. These trials were similar to the experimental trials.

1. Addition. A two-digit number and a three-digit number were presented on the screen with a plus symbol between them. The participants were asked to vocally respond with the exact answer to the equation. The operands of the equation were selected randomly, with the small operand presented on the left of the screen and the large operand presented on the right of the screen. Sixteen equations were presented.

2. Subtraction. A two-digit number and a three-digit number were presented on the screen with a minus symbol between them. All the other parameters were identical to the previous addition test.

3. Fraction addition. A pair of fractions was presented on the screen with a plus symbol between them. All the other parameters were identical to the previous addition test.

4. Fraction subtraction. A pair of fractions was presented on the screen with a minus symbol between them. All the other parameters were identical to the previous addition test.

5. Comparison of fractions. Two fractions were presented on the screen, one on the left side and the other on the right. The participants were asked to decide whether the left one was larger, the right was larger, or whether the two fractions were of the same numerical value (i.e., 1/2 vs. 3/6). They were asked to indicate their decision by pressing a left, right, or middle key, respectively. A total of 10 pairs were presented; two pairs contained fractions with the same numerator, two pairs with the same denominator, three pairs that differed both in numerator and denominator, and three pairs with identical numerical values. Every such pair was presented twice—the second time with fractions presented in a reversed order.

The accuracy rate and the RTs from the training phase were not included in the analysis.

The arithmetic tasks were based on the same principles as the mathematical ability test (diagnostic tool). We selected subtasks that presented the highest significant difference between the two groups in a previous study (see Ashkenazi & Henik, 2010a). These arithmetical tasks were computerized, while our diagnostic tests were paper-and-pencil tests. The use of computerized tasks demanded more attention and working memory than paper-and-pencil tests. Moreover, multidigit equations involve a strong need for visuospatial attention.

Training task. Participants were trained in a video game entitled “Call of Duty.” Call of Duty provides the experience of World War II’s epic battlefield through the eyes of citizens and soldiers. The player experiences authentic squad movements and tactics. The player has 24 mission objectives with a variety of weapons, locations, vehicles, and sounds. The player has to give speeded responses, become expert in the accurate use of weapons, map new spaces, and deal with multiple targets. Participants are disqualified once they fail in a mission. Note that there was no direct involvement of arithmetical knowledge in the game (as in the numerical task and enumeration task) and no involvement of spatial arrays (as in the ANT task).

On the first day of the experiment, participants were given the pre training tests. The following day the participants carried out the video game training, which started with a short training stage after receiving the examiner’s instructions regarding the game. After this stage, the participants played for 2 hours a day, every day for 10 days. A day after the last day of the training, participants received the post test. The experiment was run for a total of 14 days, with 2 day breaks (i.e., during Saturdays).

After 10 days of training, we tested the DD and the control groups in attention and numerical functioning.

Results

ANT-I Task

RT analysis. The error rates of the two groups were very small (3% for the DD group and 2% for the control group) and therefore were not analyzed. For every participant in each condition, mean RT was calculated for correct trials that were between 200 ms and 2,000 ms. These mean RTs were subjected to a five-way analysis of variance (ANOVA) with group as the only between subject factor and congruity (congruent vs. incongruent), alertness (no-tone vs. tone), cueing (invalid, noncued, valid), and training (pre vs. post training) as within subject factors.

Four of the main effects were significant. 1) Participants were faster to respond post training, \( F(1, 16) = 8.355, \text{MSE} = 10.571, p < .05, \text{partial } \eta^2 = .33 \) (606 ms pre training and 572 ms post training). 2) Participants were faster to respond on trials on which the flanker and center arrows were congruent (an effect of executive functions), \( F(1, 16) = 191.99, \text{MSE} = 4,663, p < .01, \text{partial } \eta^2 = .92 \). 3) Participants responded faster on trials with the alerting tone, \( F(1, 16) = 22.87, \text{MSE} = 1,832, p < .01, \text{partial } \eta^2 = .64 \). 4) Participants were faster on validly cued locations (an effect of orienting), \( F(1, 16) = 72.93, \text{MSE} = 787, p < .01, \text{partial } \eta^2 = .8 \).

As predicted by Callejas et al. (2004), the interaction between alertness and congruity was significant, \( F(1, 16) = 15.62, \text{MSE} = 575, p < .001, \text{partial } \eta^2 = .52 \); the congruity effect was larger in
the tone trials than in the no-tone trials. A significant interaction was also found between cueing and congruity, $F(2, 32) = 13.12$, $MSE = 667, p < .001$, partial $\eta^2 = .43$. This two-way interaction was part of a higher interaction that will be described in what follows. The interaction between alertness and cueing was also significant, $F(2, 32) = 10.765$, $MSE = 580, p < .001$, partial $\eta^2 = .4$. The congruity effect was larger in the condition with a tone in comparison with the condition without a tone.

The interaction between alertness and congruity was modulated by group, $F(1, 16) = 4.5, MSE = 575, p < .05$, partial $\eta^2 = .25$. The tone speeded up responding to the congruent condition more than to the incongruent condition. This tendency was larger in the DD group compared with the control group, $F(1, 16) = 4.53, MSE = 574, p < .05$ (see Figure 1).

**Training modulated three main areas.** First, training modulated the orienting of attention (the validity effect), $F(2, 32) = 4.618, MSE = 573, p < .01$, partial $\eta^2 = .22$. The difference between the invalid and valid conditions decreased as a result of training, $F(1, 16) = 10.38, MSE = 495, p < .01$; pre RTs for the valid condition were 569 ms and for invalid Condition 631 ms, and the validity effect was 62 ms, while post RTs for the valid condition were 549 ms and for invalid Condition 592 ms, and the validity effect was 43 ms. The interaction between training and validity was not modulated by group. Second, training modulated alertness: the triple interaction between alertness, group, and training was part of a higher interaction that will be described in what follows. The interaction between alertness and cueing was also marginally significant, $F(1, 16) = 3.69, MSE = 1.126, p = .07$, partial $\eta^2 = .16$. It seems that the difference between the two groups in the alertness system (tone effect) was larger pre training than post training. The effect of the tone was marginally larger in the DD group pre training, $F(1, 16) = 3.02, MSE = 1.276, p = .099$. In contrast, the tone effect post training was comparable between the two groups, $F < 1$ (see Figure 2).

Third, the four-way interaction between group, cueing, congruity, and training was significant, $F(2, 33) = 3.2, MSE = 391, p = .05$, partial $\eta^2 = .16$. This indicates that training eliminated the abnormal interaction between the orienting system and the executive function system that was presented in the DD group before training. As can be seen in Figure 3, the control group showed a congruity effect that was comparable for valid and noncued conditions and that was smaller (in both conditions) than in the invalid condition. This was true regardless of training. In contrast, during pre training the DD group showed a small congruity effect in the valid condition and an enlarged congruity effect in both noncued and invalid conditions. Post training they presented the same pattern as the control group. That means that the congruity effect in the noncued trials was larger in the DD group before training compared with the one of the control group. Post training, the congruity effect in the noncued trials was similar in the two groups. This was corroborated by the statistical analyses.

The congruity effect in the control group was larger in the invalid trials compared with the noncued and the valid trials, $F(1, 16) = 5.5, MSE = 836, p < .05$, and was similar in the noncued and the valid trials, $F < 1$. This interaction was not modulated by the training, $F < 1$. In contrast, in the DD group the interaction between cueing and congruity was modulated by the training, $F(2, 16) = 4.82, MSE = 397, p < .05$. Pre training, the DD group presented a different pattern than post training; the congruity effect was similar in the noncued and the invalid trials, $F < 1$, and it was smallest in the valid condition compared with the noncued and the invalid conditions, $F(1, 16) = 13.43, MSE = 445, p < .01$. Post training, the DD group presented a similar pattern as the controls. This means that the congruity effect was larger in the invalid trials compared with the noncued and the valid trials, $F(1, 16) = 17.55, MSE = 743, p < .01$. In particular, the congruity effect was similar in the noncued and the valid trials, $F < 1$.

![Figure 1](image1.png)  
**Figure 1.** RTs as a function of group, alertness, and congruency in the ANT-I task. Standard error represents standard deviation/square N.

![Figure 2](image2.png)  
**Figure 2.** RTs as a function of group, alertness, and training (pre versus post training) in the ANT-I task. *p < .05. Standard error represents standard deviation/square N.

![Figure 3](image3.png)  
**Figure 3.** Effect in ms (incongruent – congruent) as a function of group, validity, and training (pre versus post training) in the ANT-I task. An asterisk indicates a significant difference (*) $p < .05$ between the performance of the DD group and the control group. Standard error represents standard deviation/square N.
The pattern of effects pre training replicated previous results. The control results replicated those reported by Callejas et al. (2004) and Ashkenazi and Henik (2010a), and the DD results replicated those reported Ashkenazi and Henik (2010a).

Finally, we examined the influence of Z transformation on our data. As can be seen from the main effects, the general RTs in the ANT-I post training were lower compared with RTs pre training, which could possibly explain the effect of training. To rule out this possibility, we examined all the significant and marginally significant effects after Z transformations. All the significant effects remained significant after the Z transformations, except for the four-way interaction between group, cueing, congruity, and training, which became marginally significant. In addition, the triple interaction between alertness, group, and training was marginally significant and stayed marginally significant after the Z score transformation.

Numerical Operations

Accuracy analysis. Accuracy (ACC) rates were submitted to an ANOVA with two independent variables: training (pre or post training) as a within subject variable, and group (DD vs. control) as a between subject variable. Separate analyses were performed for the various tasks: addition, subtraction, fraction comparison, fraction addition, and fraction subtraction.

Training improved performance regardless of group only in addition, $F(1, 16) = 5.55$, $MSE = 0.017$, $p < .05$, partial $\eta^2 = .28$. Moreover, the effect of group was significant or marginally significant for all operations but fraction subtraction; $F(1, 16) = 4.03$, $MSE = 0.05$, $p = .06$, partial $\eta^2 = .22$, $F(1, 16) = 4.21$, $MSE = 0.04$, $p = .06$, partial $\eta^2 = .24$, $F(1, 16) = 7.29$, $MSE = 0.08$, $p < .05$, partial $\eta^2 = .33$, and $F(1, 16) = 9.33$, $MSE = 0.01$, $p < .01$, partial $\eta^2 = .37$, for addition, subtraction, fraction addition, and fraction comparison, respectively (see Table 4).

RT analysis. The RTs of the correct trials were submitted to an ANOVA with two independent variables: training (pre or post training) as a within subject variable, and group (DD vs. control) as a between subject variable. Separate analyses were performed for the various tasks: addition, subtraction, fraction comparison, fraction addition, and fraction subtraction.

There was no effect for the training in the two groups. However, for fraction addition and subtraction there were main effects of group; $F(1, 16) = 12.59$, $MSE = 3,552,328$, $p < .01$, partial $\eta^2 = .26$, and $F(1, 16) = 10.48$, $MSE = 6,585,692$, $p < .05$, partial $\eta^2 = .4$. For addition and subtraction, respectively. In both cases, the DD participants were slower than controls (see Table 4).

Enumeration

RT analysis. As depicted in Figure 4, the DD group had a subitizing range of three items, compared with four items in the control group, regardless of training. RT rose sharply between three and four items in the DD group but not in the control group. Yet, training speeded up responding to one to three dots in the DD group but not in the control group in the random arrangement condition. In addition, in the canonical arrangement condition, the DD participants were faster post training compared with pre training. We carried out planned comparisons to corroborate these observations. For the subitizing range up to three dots, there was no difference between the two groups ($F < 1$ for all the comparisons). The DD participants responded slower than controls to four dots in a random condition, $F(1, 14) = 5.42$, $MSE = 21,543$, $p < .05$, partial $\eta^2 = .24$, and the difference between the groups in the canonical presentation was marginally significant, $F(1, 14) = 3.74$, $MSE = 2.247$, $p = .07$, partial $\eta^2 = .13$. In addition, DD participants were slower to respond to four dots than to three dots in the random arrangement, $F(1, 14) = 15.15$, $MSE = 12,187$, $p < .01$, partial $\eta^2 = .56$, whereas controls showed no such difference, $F < 1$.

Similar to Green and Bavelier (2003), we examined the training effect for every group and every arrangement separately. The results indicated a larger influence of training on the DD group, especially in the canonical condition. The DD group was faster in all canonical arrangements post training than pre training; $F(1, 8) = 19.3$, $MSE = 25,025$, $p < .01$, partial $\eta^2 = .64$, $F(1, 8) = 9.377$, $MSE = 5,556$, $p < .05$, partial $\eta^2 = .31$, $F(1, 8) = 18.94$, $MSE = 1,254$, $p < .01$, partial $\eta^2 = .39$, $F(1, 8) = 28.5$, $MSE = 296$, $p < .01$, partial $\eta^2 = .73$, $F(1, 8) = 28.5$, $MSE = 6,239$, $n$s, partial $\eta^2 = .21$, $F(1, 8) = 12.84$, $MSE = 2,016$, $p < .01$, partial $\eta^2 = .64$, $F(1, 8) = 14.43$, $MSE = 7,180$, $p < .01$, partial $\eta^2 = .67$, $F(1, 8) = 5.54$, $MSE = 19,531$, $p = .06$, partial $\eta^2 = .42$, $F(1, 8) = 6.57$, $MSE = 39,089$, $p < .05$, partial $\eta^2 = .48$, for the canonical presentation of one through nine dots.

<table>
<thead>
<tr>
<th>Group</th>
<th>Operation</th>
<th>Pretraining</th>
<th>Posttraining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy %</td>
<td>Reaction time (ms)</td>
<td>Accuracy %</td>
</tr>
<tr>
<td>DD</td>
<td>Addition</td>
<td>66 (22)</td>
<td>7,541 (4,842)</td>
</tr>
<tr>
<td></td>
<td>Subtraction</td>
<td>65 (17)</td>
<td>9,432 (5,913)</td>
</tr>
<tr>
<td></td>
<td>Addition of fractions</td>
<td>60 (36)</td>
<td>5,535 (2,207)</td>
</tr>
<tr>
<td></td>
<td>Subtraction of fractions</td>
<td>85 (30)</td>
<td>5,628 (2,286)</td>
</tr>
<tr>
<td></td>
<td>Fraction comparison</td>
<td>74 (18)</td>
<td>2,865 (662)</td>
</tr>
<tr>
<td>Controls</td>
<td>Addition</td>
<td>83 (22)</td>
<td>4,596 (2,418)</td>
</tr>
<tr>
<td></td>
<td>Subtraction</td>
<td>82 (14)</td>
<td>6,082 (4,268)</td>
</tr>
<tr>
<td></td>
<td>Addition of fractions</td>
<td>94 (4)</td>
<td>3,691 (1,527)</td>
</tr>
<tr>
<td></td>
<td>Subtraction of fractions</td>
<td>95 (10)</td>
<td>2,838 (921)</td>
</tr>
<tr>
<td></td>
<td>Fraction comparison</td>
<td>88 (11)</td>
<td>1,664 (751)</td>
</tr>
</tbody>
</table>
respectively. Notice that training did not affect five dots and had a marginal effect on eight dots.

In the random condition, the influence was restricted to the DD subitizing range (i.e., 1–3 dots), $F(1, 8) = 16.4, MSE = 1,450, p < .01$, partial $\eta^2 = .7$, $F(1, 8) = 6.16, MSE = 5,556, p < .05$, partial $\eta^2 = .46$, and $F(1, 8) = 10.12, MSE = 3,136, p < .05$, partial $\eta^2 = .59$, for one, two, and three dots, respectively. Training did not modulate performance of the control group regardless of range and dot arrangement. The RTs of the control group were similar pre and post training for the two arrangements (see Figure 4).

Accuracy analysis. As can be seen in Figure 5, there was no effect of training on either group with any arrangement. In addition, the subitizing range of the two groups was four dots and was not modulated by training. The statistical analysis corroborated these observations (i.e., the relevant statistical comparisons were not significant).

Discussion

Summary of the main results:

1) Training reduced the validity effect of the spatial cue in both groups.

2) Training seems to alleviate the attention deficit in those with DD. First, training reduced the enlarged congruity effect—post training the congruity effect was comparable in the two groups. Second, training modulated the differences in the alertness effect—DD participants presented marginally significant larger alertness effect pre training, but this became similar to that of controls post training.

3) Training improved enumeration in the DD group: a) in the subitizing range—up to three dots, regardless of dot arrangement, and b) in the counting range for the canonical dot arrangement. Training had no effect on a) the subitizing range of the DD participants, which was three (RT to four dots was higher than RT to three dots but was not affected by training), and b) on enumeration in the controls.

4) Training improved accuracy in addition problems in both groups.

The main aim of the present study was to examine the question whether DD involves a domain-general or domain-specific disorder. There are indications that “pure” DD participants (those with no comorbidity) presented deficits in attention, despite not meeting criteria for ADHD (Ashkenazi & Henik, 2010a, 2010b). If the deficits in attention directly influence the deficits in numerical processing among those with DD then improvement in attention (by attention training) should improve numerical processing in the DD group more than in the control group. However, the results of the present study do not support this suggestion: attention training in the DD group improved attention but did not specifically improve numerical processing. In the next section we will discuss these issues.

Reduced Attentional Deficits in DD

Previously DD participants presented deficits in two attentional systems; the executive system—indicated by a large congruity effect—and the alertness system—indicated by a larger effect of tone. Moreover, these two aspects of attention interacted signifi-
In the present study the interaction between group, validity, congruity, and training was significant. Specifically, the DD group showed a larger congruity effect than the control group pre training. Training eliminated the difference in congruity between the two groups.

Similarly, the DD group showed a larger alertness effect compared with the control group pre training. This difference between the two groups was eliminated post training.

The fact that the attentional deficit changed after ten days of training might suggest that the deficit was not major in the first place. Moreover, the fact that improvement in attention did not induce an improvement in numerical processing might suggest these two difficulties are attributable to different causes. Note that the latter suggestion is not in line with the domain-general hypothesis (Geary, 1993). However, even though in the adult brain attention and numerical deficits seem decoupled, one cannot rule out the possibility that in early or mid childhood, attention difficulties among those with DD lead to arithmetic difficulties. To fully understand the connections between deficits in attention and numerical processing among the DD population, one should examine attention and numerical trajectories during development rather than in the adult brain (Karmiloff-Smith, 2008).

Training Effects on Subitizing

Green and Bavelier (2003) presented random ordered squares ranging from 1 to 12 for short presentation times (i.e., 50 ms) and examined changes in accuracy rate attributable to video game playing. They found that video game playing enlarged the subitizing range and improved accuracy rate in general. The present study examined the influence of playing video games on the subitizing range in DD participants. We used longer presentation times (i.e., 200 ms) than Green and Bavelier did and added a canonical arrangement condition. We did not find an increase in the subitizing range among DD participants; they had a smaller subitizing range (i.e., three dots) than the controls pre and post training. In addition, the subitizing range of controls was not modulated by training. Still, the DD participants were faster in their subitizing range (of three dots) post training in comparison with pre training. Canonical arrangements commonly show a perceptual advantage relative to random arrangements and accordingly, the DD group displayed improvement attributable to training throughout the range of the canonical displays. It is possible that the differences between our study and Green and Bavelier’s were related to differences in exposure duration (longer in our study because participants suffered from DD).

Two features characterize DD performance in the subitizing range: first, a smaller subitizing range, and second, slower responding. The range was not modulated by training whereas speed of responding was. Hence, it seems that the major difficulty (i.e., smaller subitizing range) of DD is not modulated by attention. In contrast, speed of processing seems to be favorably affected by attentional training.

Training Effects on Arithmetic

The triple-code model of number processing suggests the existence of three distinct systems of numerical representation: a quantity system—a nonverbal semantic representation of the size and distance relations between numbers, which may be category-specific; a verbal system—where numerals are represented lexically, phonologically, and syntactically much like any other type of word; and a visual system (Dehaene & Cohen, 1995; Dehaene et al., 2003). According to the model, different operations require activation of different brain regions. For example, subtraction, number comparison and division activate the quantity system (i.e.,
the IPS) more than multiplication and addition do. In contrast, addition and multiplication activate the left angular gyrus (which is part of the verbal system and is not specifically related to numerical processing) and rely on retrieval of arithmetical facts more than subtraction, division, and number comparison do. In the current study, training improved addition but not subtraction, regardless of group. As mentioned above, addition relies more on the verbal system and hence is less dependent on the quantitative system. Accordingly, it might be more affected by nonspecific attentional training. However, to achieve high ecological validity, we examined the effect of attention training on arithmetic with multidigits and fraction equations. Solving of those equations involves working memory load and visuospatial attention. Accordingly, it is hard to decide which aspects of enhanced attention, as a result of video game training, improved the accuracy of the addition equations.

Does Attentional Training Benefit Those With DD?

Certain deficits in attention in the DD group (e.g., executive and alertness tasks) improved after attentional training. In contrast, much of the numerical performance (e.g., subitizing range, arithmetic) did not change specifically in the DD group. One explanation could be that the attentional deficit and the numerical problems have different sources. In that case, improving of one kind of ability should not influence improvement in the other. This view can be supported by a recent MRI study (Rotzer et al., 2008) that found abnormalities in gray matter volume of the DD participants compared with controls in frontal sites, believed to be a part of the executive network, and in the right IPS, believed to be related to numerical processing. It is possible that difficulties in attention and calculation have different sources. However, Rotzer et al. (2009) reported that deficits in the IPS (believed to be the origin of the numerical deficits in DD) were related to working memory deficiencies in DD. The latter result fits the notion that DD reflects a domain-general disorder. The domain-general hypothesis claims that nonspecific difficulties (e.g., attention) are the basis of numerical deficits. The result of the present study hints that DD is not uniquely a domain-general disorder. It is possible that those with DD suffer from a unique numerical deficit in addition to attentional deficits. The latter may add to and exacerbate the numerical difficulties.

Video Games Improve the Orienting of Attention

There is converging evidence that video game playing improves attention. Recently, Dye et al. (2009) used the ANT (Fan et al., 2002) to examine the influence of playing video games on three attention networks. The results indicated that video games players (VGP) had a larger orienting effect compared with nonplayers (NVGP). Moreover, the congruity effect was larger among VGP compared with NVGP. This study is different from our study in several ways. First, Dye and colleagues recruited participants who were video game players; they did not have any training during the study itself. In contrast, our participants were naïve and received video game training at the beginning of the study. Second, Dye and colleagues used the ANT whereas we used the ANT-I (Callejas et al., 2004). The ANT and ANT-I differ in the way they measure orienting of attention. The ANT measures endogenous attention whereas ANT-I measures exogenous attention (Berger, Henik, & Rafal, 2005; Rafal & Henik, 1994). Importantly, endogenous (i.e., predictive) cues encourage participants to use the information provided by the cue, whereas exogenous cues are not predictive and participants are told that they can be ignored. In the present study, after training, participants were more able to ignore the noninformative cue. In contrast, in Dye and colleagues’ study, video game playing seemed to improve the ability to orient attention according to predictive cues. To sum up, it seems that video game training improves the ability to selectively pay attention to the environment. Specifically, it improves the ability to ignore noninformative information and at the same time to deploy attention resources in informative information.

Clinical Implication and Limitations

The present study found that nonspecific training (e.g., attentional training) did not improve the core deficit of DD. Hence, it is probable that those with DD require specific training in numerical processing; attentional training is not sufficient. However, one should remember the sample size of the present study: because of the rareness of pure DD, our sample size was nine participants. It would be important to replicate the present study with a larger DD group and examine the effect of attention training on a group with comorbidity between ADHD and DD. Moreover, the present study tried to achieve high ecological validity by using action video game training instead of a specific attention training program. Furthermore, the video game training only lasted ten days. Additionally, in the enumeration task, vocal RTs were measured and then the experimenter keyed in the answer of the participants to examine accuracy. This extended the time between trials and possibly influenced the results. Moreover, the present study examined arithmetic by using multidigit or fraction computerized equations that demand high working memory load and executive function attention. It might be important to examine the current questions with specific attention training and more basic arithmetic (such as retrieval of arithmetical facts).

Conclusions

Attentional training using video games improved deficits in attention. However, attention training did not improve specific deficits in numerical processing among those with DD.

Because of these facts, the current study, along with previous studies (Ashkenazi & Henik, 2010a, 2010b), indicates that individuals with developmental disorders present aspects of deficits that are domain-general. However, domain-general aspects (e.g., attention) cannot uniquely explain the specific numerical processing deficit in DD because attention training did not specifically improve numerical ability in those with DD.

References


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