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Attention, Automaticity, and Developmental Dyscalculia

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People suffering from developmental dyscalculia (DD) show an abnormal pattern of the *size congruity effect*. They do not display a facilitation component in a numerical Stroop task. In this task, participants are presented with 2 digits that differ both in physical size and numerical value, and they have to compare the digits while ignoring one of the dimensions. The present study examined performance of those with DD and control participants in the numerical Stroop task under cognitive load. The no-load condition replicated previous findings (i.e., lack of facilitation in the physical task for the DD group). Load had opposite effects on interference and facilitation. Load eliminated facilitation and increased interference in the control group. Load increased interference only in the physical task in the DD group. The opposite effect of load on facilitation and interference suggests that these components are related to different cognitive mechanisms. The fact that load produced a DD-like pattern in the control group could suggest that individuals with DD suffer from difficulty in recruiting attention in addition to the deficits in numerical processing.

Keywords: size congruity, numerical Stroop, cognitive load, interference, facilitation

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Developmental dyscalculia (DD) is a disorder in mathematical abilities presumed to be due to a specific impairment in brain function (Rubinsten & Henik, in press; von Aster & Shalev, 2007; Wilson & Dehaene, 2007). DD is supposed to be a unique deficit, not caused by a reading disorder (dyslexia), attentional disorder (attention-deficit/hyperactivity disorder [ADHD]), or general intelligence problems. The present work investigated deficits in attention in DD participants employing a numerical Stroop task and manipulating cognitive load.

Developmental Dyscalculia and Attention

Children with DD fail in a wide range of numerical tasks. For example, they present difficulties in retrieving arithmetical facts (Kaufmann, Lochy, Drexler, & Semenza, 2004; Temple, 1991; Wilson & Dehaene, 2007), using arithmetical procedures (e.g., Temple, 1991), and solving arithmetical operations (Geary, Hamson, & Hoard, 2000). Recently, studies of DD have concentrated on basic numerical processing and have indicated difficulties in several processes: magnitude comparison (Geary et al., 2000), subitizing (Koontz & Berch, 1996), and implicit processing of quantities (Rubinsten & Henik, 2005, 2006).

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Comorbidity of ADHD and DD is not infrequent (Rubinsten & Henik, in press). Recent estimates suggest that 25% of children with ADHD have a comorbid mathematics disorder (Mayes & Calhoun, 2006). It is interesting that comorbidity of DD and ADHD is larger than the comorbidity of DD and other learning disabilities (e.g., dyslexia; R. L. Lindsay, Tomazic, Levine, & Accardo, 2001).

ADHD is characterized by a deficit in self-regulation, poor attentional control, and poor response inhibition. It has been suggested that all of these deficits are based on deficits in executive processes supported by the frontal lobes (e.g., Castellanos, Sonuga-Barke, Milham, & Tannock, 2006). Arithmetical disabilities in ADHD are considered to be connected to poor working memory abilities and other executive functions (e.g., Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; but see recent work by Kaufmann & Nuerk, 2008).

The Numerical Stroop Task

People suffering from DD show deficiency in performing a numerical Stroop task (Rubinsten & Henik, 2005, 2006). In this task, participants are presented with two digits that differ both in physical size and numerical value, and are asked to compare the physical sizes of the digits and ignore their numerical values or to compare the numerical values and ignore the physical sizes. Under these conditions, it is common to find a *size congruity effect* (SCE; Henik & Tzelgov, 1982) composed of *facilitation*—faster responding to congruent (e.g., 3 6) than to neutral (e.g., 3 3 for physical comparisons or 6 3 for numerical comparisons) trials—and *interference*—slower responding to incongruent (e.g., 3 6) trials than to neutral trials. Most important, for the physical comparisons, this effect means that numerical values are processed automatically even when they are irrelevant and interfere with performance.

The SCE changes with practice (Tzelgov, Henik, Yehene, Kotler, & Alon, 2000) and schooling (Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). In particular, Rubinsten et al. (2002) found no SCE in physical comparisons at the beginning of first grade and an interference-based SCE with no facilitation at the end of first grade. An adult-like pattern of SCE was found in third grade and on. Accordingly, it was suggested that first-grade children showed no indication of automatic activation of the numerical values of Arabic numerals. In two recent studies, Rubinsten and Henik (2005, 2006) reported that college students suffering from DD showed a pattern similar to that shown by children at the end of first grade; namely, the students did not produce facilitation in physical comparisons and showed an overall reduction in SCE. An SCE that lacked facilitation was also found in nondeficient students after a transcranial magnetic stimulation to the right intraparietal sulcus (IPS) but not to the left IPS (Cohen Kadosh et al., 2007). In addition, absence of a facilitation component was recently reported in acquired dyscalculia (Ashkenazi, Henik, Ifergane, & Shelef, 2008). It is interesting that Kaufmann and Nuerk (2006) reported a difference between ADHD and control participants in SCE and suggested that the basis of the presented deficits was inhibitory control due to the proximity of brain areas involved in number processing and visual attention.

The Current Study

We examined potential attention failures in DD. To this end, we employed the numerical Stroop task and manipulated cognitive load in DD participants and normal controls. We manipulated attentional load by adding a secondary task to the primary task (e.g., Lavie, 2005).

One of the early definitions of *automaticity* is that a process is automatic if it is resource free (e.g., Hasher & Zacks, 1979: Shiffrin & Schneider, 1977). For example, in a feature search (e.g., searching for an *S* among *T*s and *X*s), the target shares only one dimension with the distractors and responding is independent of the number of distractors. In contrast, in a conjunction search (e.g., searching for a red *S* among red *T*s and green *S*s), the target shares more than one feature with the distractors and responding slows down with an increase in the number of distractors. Feature search is considered to be automatic and load free, whereas a conjunction search requires attention to be executed (Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989). Accordingly, we manipulated attention demands using a dual task design; namely, we examined effects of a secondary conjunction task on performance of the primary numerical Stroop task.

With the normally developing (control) participants, we examined whether the SCE could be modulated by cognitive load. We hypothesized that under cognitive load, controls would present a DD-like pattern of results (e.g., a reduced facilitation component). With DD participants, we asked whether attentional load would be detrimental to their performance: Would they present a change in the interference component of the SCE and not only a lack of facilitation that they present under a no-load condition? Moreover, there are indications that individuals with DD are slower than normally developing participants in number comparisons but not with physical size comparisons (e.g., Rousselle & Noël, 2007). Accordingly, we hypothesized that DD participants would be slower than controls in the numerical task but not in the physical task. We are not implying that participants with DD suffer only from attentional deficits. We suggest that in addition to a deficit in number processing, abnormal attention may also contribute to the deficiency.

Method

In each trial, participants were presented with two digits and two figures, one to the left and one to the right of the two digits. In the load condition, participants were asked to compare the digits (primary task) and also to compare the two peripheral figures (secondary task). In a typical trial, participants first indicated which digit was larger and then vocally reported whether the two figures were identical or different. The two digits and the two figures disappeared simultaneously on onset of the vocal response. The no-load condition was identical in presentation, but participants were asked to perform only the primary task (i.e., digit comparison).

Participants

Twenty-six students from Ben-Gurion University of the Negev participated in the experiment. Thirteen were diagnosed as having DD according to Rubinsten and Henik's (2005, 2006) criteria (see also the supplementary material), and 13 were age- and sex-matched controls. The controls did not have any learning or other disabilities. All students were paid 60 NIS ($15) for participation in the experiment.

Stimuli and Design

Physical (numerical values irrelevant) and numerical (physical sizes irrelevant) comparisons were carried out in separate blocks in two attentional conditions: no-load condition and attentional load condition. A given block contained equal numbers of congruent (e.g., 6 3), incongruent (e.g., 3 6), and neutral stimuli. Neutrals were composed of two digits that differed only on the relevant dimension (e.g., 6 6 in the physical comparisons, 6 3 in the numerical comparison).

Each trial was composed of two Arabic digits at the center of a computer screen and two figures (7/8^{ths} of a circle, such as these: ) at the periphery of the screen (5 degrees from the center of the screen, one on each side). The open circles could differ in color or in orientation of the opening. For example, the color could be different but the orientation identical, the color could be identical but the orientation different, or the color and orientation could be identical.

The following variables were manipulated: group (DD vs. control), task (physical, numerical), numerical distance (1, 3, or 5), congruity (incongruent, neutral, or congruent), and attention (load vs. no load). Thus, we had a $2 \times 2 \times 3 \times 3 \times 2$ factorial design. Group was the only between-participants variable; task and attention conditions were manipulated within participants but between blocks, and distance and congruity were manipulated within block.

Procedure

Every participant was tested twice, once in the no-load condition and once in the load condition, with a minimum of 3 days and maximum of 2 weeks break between the two sessions. The order of the sessions was counterbalanced between participants for each group.

In the load condition, participants performed a digit comparison (primary task) followed by a figure comparison (secondary task). Participants indicated their comparative judgment decision by a key press and then vocally reported whether the two open circles were identical or not. In the no-load condition, stimuli were identical to those in the load condition, but participants were instructed to perform only the primary task.

Each trial began with a fixation asterisk for 300 ms. The fixation disappeared, and two open circles appeared in the periphery. One hundred ms after the onset of the circles, two digits appeared at the center of the screen. Participant responded with a key press to the numbers, followed by a vocal response to the circle, after which the number and circles disappeared. The next trial began 1,000 ms after the participant's response. Reaction time was measured in milliseconds from target onset to participant's key press.

Results

Error rates in the primary task were generally low (see supplementary material) and were not analyzed. Only the "different" responses in the secondary task were analyzed to prevent inclusion of trials with a pop-up (see supplementary material). Mean reaction time was calculated for every participant in each condition (only for the correct trials in the primary and the secondary tasks). These means were subjected to planned comparison analyses.

We expected the DD group to lack the facilitation component (i.e., congruent vs. neutral trials) in the physical task under the no-load condition. Hence, we analyzed each task separately. In addition, we suggested earlier that for control participants attentional load may produce a difficulty in recruiting attention and result in a similar effect (i.e., lack of facilitation) under the load condition. We also expected the DD group to be slower than the controls in the numerical task but not in the physical task. The results supported these suggestions.

Facilitation

In the physical task, DD participants did not present a significant facilitation component, regardless of load (both comparisons Fs < 1). In contrast, in the physical task, the control group presented a significant facilitation component, $F(1, 12) = 5.01$, $\eta_p^2 = .29$, $MSE = 147$, $p < .05$, under the no-load condition, and no facilitation component under the attentional load condition ($F < 1$; see Table 1 and Figure 1).

We tested the facilitation in the numerical task and found that under load the control participants did not present the facilitation component ($F < 1$), whereas DD participants presented facilitation, $F(1, 12) = 6.88$, $\eta_p^2 = .36$, $MSE = 5{,}453$, $p < .05$. In the no-load condition, both groups presented the typical facilitation component: DD, $F(1, 12) = 9.38$, $\eta_p^2 = .44$, $MSE = 3{,}712$, $p < .01$, and controls, $F(1, 12) = 6.85$, $\eta_p^2 = .36$, $MSE = 1{,}769$, $p < .05$.

Interference

We examined the influence of load on the interference component. The control group showed larger interference under the load condition than under the no-load condition for both the physical and numerical tasks, $F(1, 12) = 7.04$, $\eta_p^2 = .24$, $MSE = 7{,}272$, $p < .05$. The DD participants, in contrast, showed a larger interference component under attentional load than under the no-load condition only for the physical task, $F(1, 12) = 36.4$, $\eta_p^2 = .75$, $MSE = 1{,}341$, $p < .01$ (see Table 1 and Figure 1).

In addition, the difference in reaction times between the groups was larger in the numerical task (814 ms and 730 ms for the DD and control participants, respectively) than in the physical task (611 ms and 620 ms for the DD and control participants, respectively), $F(1, 24) = 4.6$, $\eta_p^2 = .16$, $MSE = 108{,}126$, $p < .05$.

Note that all effect sizes (η_p^2) mentioned above can be interpreted as large effect sizes.

Table 1
Effects in the Numerical and Physical Tasks

Condition	Effect	Group DD	Group Control
Physical task			
No load	Facilitation	6	11*
	Interference	17*	21**
	Congruity	23**	32**
Attentional load	Facilitation	−13**	1
	Interference	88**	104**
	Congruity	75**	105**
Numerical task			
No load	Facilitation	42**	25*
	Interference	81**	52**
	Congruity	124**	77**
Attentional load	Facilitation	44*	−6
	Interference	84**	72**
	Congruity	128**	65**

Note. DD = developmental dyscalculia. The congruity effect is the difference between incongruent and congruent conditions. The facilitation component is the difference between neutral and congruent trials. The interference component is the difference between incongruent and neutral trials (e.g., the mean reaction times of DD participants in the no-load condition in the physical task were as follows: incongruent = 406 ms, neutral = 389 ms, congruent = 383 ms. Accordingly, their facilitation equals 389 – 383 = 6 ms, their interference equals 406 – 389 = 17, and their congruity effect equals 406 – 383 = 23 ms).
* $p < .05$. ** $p < .01$. An asterisk indicates a significant difference between the performances of the control participants and the DD participants.

Discussion

Let us summarize the main results.

1. There was no facilitation under no load in the DD group. The no-load condition replicated previous findings. In the physical comparisons, the DD participants' SCE lacked the facilitation component, whereas in the numerical comparisons, they presented a SCE that was composed of both facilitation and interference. The control group presented significant facilitation and interference in both tasks.
2. Load modulates facilitation. In the physical task, neither group showed facilitation under load. In the numerical task, only the controls showed no facilitation.
3. Load modulates interference. Load increased the interference component in both tasks in the control group. The DD group showed such an increase only in the physical task.

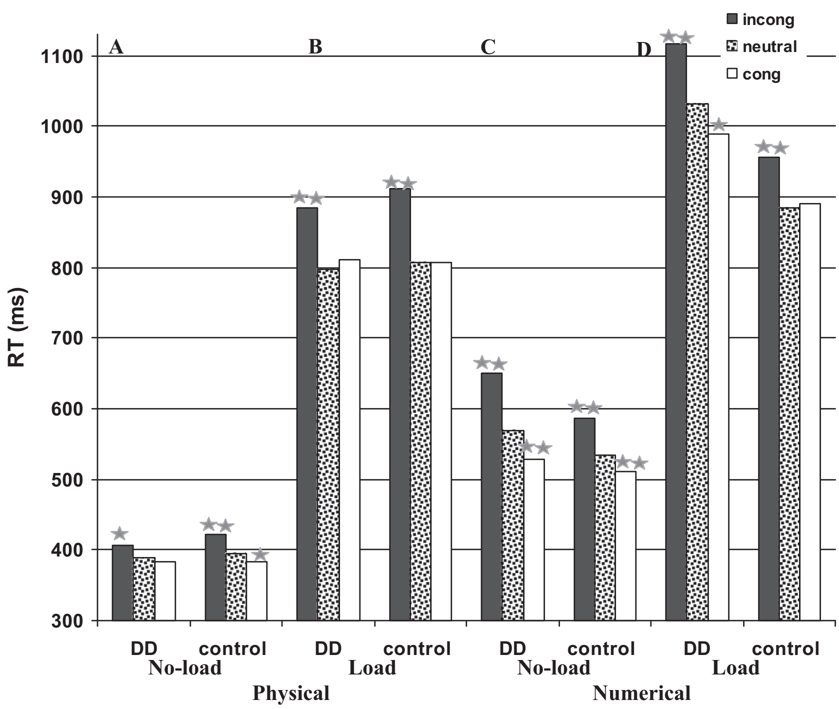

Figure 1. Mean reaction times in milliseconds as a function of load, group, task, and congruity. 1. Physical task no-load: Both groups show interference; only developmental dyscalculia (DD) participants lack facilitation (A column). 2. Physical task with load: Both groups show interference but no facilitation (B column). 3. Numerical task no-load: Both groups show interference and facilitation (C column). 4. Numerical task with load: DD participants present both facilitation and interference and controls only interference (D column). 5. The groups are not different in general reaction time in the physical task (A + B), whereas DD participants are slower in the numerical task (C + D). * $p < .05$. ** $p < .01$. An asterisk indicates a significant difference between the marked condition and the neutral condition.

4. DD participants were slower compared with the control group in the numerical task but not in the physical task.
5. All of these results (i.e., 1–4) presented large effect sizes.

Load and Selective Attention

Lavie (2005) distinguished between perceptual and cognitive or executive load. Perception has a limited capacity, and processing of stimuli continues until it runs out of capacity. Accordingly, a high-load condition engages full capacity in the relevant dimension, and no spare capacity is left to process the irrelevant distractors. In contrast, a low-load condition produces attention that is not needed for the task, and this attention "spills over" to the irrelevant distractors. The opposite is true for executive load. Executive load exists when participants have to distinguish between a target and distractors that are very similar, that is, they have to operate control to resolve the conflict between the target and the distractors. Executive load prevents prioritization of target processing and distractor inhibition. As a result, participants process the distractors more under high cognitive load compared with low cognitive load. Note that the perceptual and executive loads have opposite effects: Executive load increases processing of the irrelevant dimension, whereas perceptual load decreases processing of the irrelevant dimension. Commonly, perceptual load is manipulated in visual search tasks, and cognitive load is manipulated in dual tasks and high working memory load.

The present study used a dual task situation that results in an executive cognitive load in Lavie's (2005) terms. Thus, load should produce a larger congruity effect. However, the current results indicate a dissociation between these two components of SCE: Load increased interference and eliminated facilitation. The present study is not the first to report a dissociation between the facilitation and interference components of similar congruity effects (D. S. Lindsay & Jacoby, 1994; Tzelgov, Henik, & Berger, 1992). What is a possible explanation for this dissociation between components? It could be that the bases of the facilitation and interference components are related to different cognitive mechanisms. A recent study supports this suggestion. Szucs and Soltesz (2008) used event-related potentials to examine the facilitation and interference components of SCE. They found that the facilitation and interference components appeared at different time windows and seemed to involve different stages of processing. Within Lavie's framework, the change of interference fits in with an executive load situation, whereas the reduced facilitation is expected in perceptual load tasks. Namely, facilitation and interference may be modulated at different levels of processing or by different mechanisms. This suggests that the deficiency presented by DD participants might involve multiple mechanisms.

Specific Attentional Deficit in DD

Rubinsten and Henik (2005, 2006) found no facilitation component in adults with DD in the physical task (when the unattended dimension was the numerical value), but they found an intact congruity effect (i.e., both facilitation and interference) in the numerical task. The present study replicated this pattern in DD participants under a no-load condition. Similar results were reported recently by Ashkenazi et al. (2008) in an acquired acalculia patient.

Attentional load reduced facilitation and augmented interference in the control group in both tasks, whereas the DD group presented an abnormal pattern of SCE only in physical comparisons and not in the numerical comparisons. The lack of facilitation in the control group in the physical and numerical tasks is similar to the results of Cohen Kadosh et al. (2007). In that study, transcranial magnetic stimulation to the right IPS, but not to the left IPS, eliminated facilitation regardless of task. Considering these findings together suggests that the lack of facilitation could be the result of difficulty in recruiting attention. Note, however, that DD participants presented normal facilitation when physical size was the irrelevant dimension and lacked facilitation when numerical value was the irrelevant dimension. Accordingly, we suggest that individuals with DD have a distinctive attention problem. Specifically, they present difficulty in recruiting attention only within the numerical domain and not within the physical domain. This is in line with Rubinsten and Henik (2006), who found that individuals with DD have difficulties in associating quantities with written numbers but not sounds (phonemes) with written letters.

Previous studies with DD participants have supported the hypothesis of selective impairment in the numerical domain. For example, Rousselle and Noël (2007) discovered that DD is characterized by a deficiency in relating symbols to quantity rather than processing numerosity per se; DD participants had difficulty in comparing Arabic numbers, but no such effect was found for nonsymbolic magnitude comparisons (e.g., comparing collections of sticks). In the current study, if the difficulties of those with DD are in symbolic processing, then it is not surprising that DD participants presented a normal pattern of SCE in the numerical task.

The Influence of Load on DD

Control participants were influenced by load regardless of task (numerical or physical), whereas DD participants were not influenced by load in the numerical task. What is the reason for this pattern (no effect of load) among those with DD? It is possible that individuals with DD invest more resources in numerical comparisons compared with the controls. This, in turn, leaves no spare resources for the irrelevant (physical) dimension. There is some evidence that supports this suggestion. First, Rubinsten and Henik (2005, 2006) suggested that the connection between number symbols and their internal representation of magnitude is less automatic among individuals with DD. In addition, in the present study, DD participants were slower than controls in the numerical task but not in the physical task. Slower responding usually correlates with the difficulty of the task: Participants tend to perform easy and automatic tasks faster than controlled and hard tasks. In line with Lavie's (2005) selective attention theory, one could suggest that in more automatic processing, irrelevant information could influence performance more than in controlled processing (that demands a large amount of resources).

Conclusions

Our findings suggest that (a) SCE that is alleged to indicate automatic processing (of the irrelevant dimension) is actually modulated by cognitive load. (b) Individuals with DD seem to have difficulty with recruiting attention. Moreover, it seems that this difficulty is specific for processing numerical but not physical aspects of stimuli. (c) It is possible that individuals with DD have a deficiency in processing symbolic numerical information but not nonsymbolic numerical information.

Conclusions based on the present findings are limited by several factors. Because of the rareness of pure DD cases, we could test only a small sample of participants. However, despite this limitation, significant differences and large effect sizes were found. A replication with larger clinical samples and more extensive ADHD protocols will further reinforce these results and afford a better understanding of the role of attention in DD.

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