Do subitizing deficits in developmental dyscalculia involve pattern recognition weakness?

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Abstract

The abilities of children diagnosed with developmental dyscalculia (DD) were examined in two types of object enumeration: subitizing, and small estimation (5–9 dots). Subitizing is usually defined as a fast and accurate assessment of a number of small dots (range 1 to 4 dots), and estimation is an imprecise process to assess a large number of items (range 5 dots or more). Based on reaction time (RT) and accuracy analysis, our results indicated a deficit in the subitizing and small estimation range among DD participants in relation to controls. There are indications that subitizing is based on pattern recognition, thus presenting dots in a canonical shape in the estimation range should result in a subitizing-like pattern. In line with this theory, our control group presented a subitizing-like pattern in the small estimation range for canonically arranged dots, whereas the DD participants presented a deficit in the estimation of canonically arranged dots. The present finding indicates that pattern recognition difficulties may play a significant role in both subitizing and subitizing deficits among those with DD.

Introduction

Developmental dyscalculia (DD) is generally defined as a disorder in mathematical abilities presumed to be due to a specific impairment in brain function (Kosc, 1974; Shalev, Manor & Gross-Tsur, 1993), with no indication of reading disorder (dyslexia), attentional disorder (Attention Deficit Hyperactive Disorder – ADHD/ Attention Deficit Disorder – ADD), or general intelligence problems.

It has been suggested that the deficit in DD involves the intraparietal sulcus (IPS) (Cohen Kadosh, Cohen Kadosh, Schuhmann, Kaas, Goebel, Henik & Sack, 2007; Isaacs, Edmonds, Lucas & Gadian, 2001; Molko, Cachia, Riviè re, Mangin, Bruandet, Le Bihan, Cohen & Dehaene, 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 number sense (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 (Ashkenazi & Henik, 2010a, 2010b; Ashkenazi, Rubinsten & Henik, 2009b; Geary, 1993). For example, an MRI study (Rotzer, Kucian, Martin, von Aster, Klaver & von Aster, 2008) revealed abnormalities in gray matter volume of DD participants compared to controls in frontal sites that are believed to be a part of the executive network. Gray matter volume of the DD participants was smaller in the middle frontal gyrus bilaterally, the left inferior frontal gyrus, and the anterior cingulum bilaterally. In addition, there are indications that mathematical abilities are correlated to general abilities, such as executive functions (Bull & Scerif, 2001) and visuo-spatial working memory (Wilson & Swanson, 2001). Furthermore, the IPS is believed to be involved in visuo-spatial working memory, number processing and visuo-spatial attention (e.g. Rotzer, Loenneker, Kucian, Martin, Klaver & von Aster, 2009). Accordingly, Rotzer et al. (2009) indicated that those with DD have lower behavioral performances in non-numerical visuo-spatial working memory abilities, along with lower activity in the IPS. In the present study, we will examine whether a deficit in subitizing among those with DD is related to a domain-general mechanism such as a pattern identification weakness, or a deficit in basic numerical processing or number sense.

Object enumeration

Cognitive research differentiates between three processes that enable identification of quantities: subitizing, serial counting and estimation. Subitizing is defined as a fast and accurate assessment of a number of small quantities...
(Kaufman, Lord, Reese & Volkman, 1949). The subitizing range is between 1 to 4 dots. Responding changes with the number of dots but the increase in reaction time (RT) is smaller than 100 ms per item (Akin & Chase, 1978; Mandler & Shebo, 1982; Simon, Peterson, Patel & Sathian, 1998; Trick & Pylyshyn, 1993). Serial counting is used for a larger set of objects. In contrast to subitizing, the slope of the function is steeper; namely, RT increase is more than 250 ms per item (Akin & Chase, 1978; Mandler & Shebo, 1982; Simon et al., 1998; Trick & Pylyshyn, 1993). Estimation is an imprecise process used to assess large numbers of items for a short presentation time. Relative to subitizing, RT in estimation is less dependent on the number of items presented, and the error rates are much higher than in subitizing.

Do subitizing and estimation share mental operations and brain mechanisms? According to the magnitude hypothesis (Dehaene & Cohen, 1994), subitizing and estimation are related to the function of the analog magnitude system. In the case of small quantities, the magnitude system can estimate the exact numbers of items. In contrast, in the case of large quantities (larger than 4 items), the analog magnitude system will give only an estimation of the amount of items. This system operates according to Weber's law, that is, based on a logarithmic scale (Dehaene & Cohen, 1994) or larger variability with increased magnitudes (Gallistel & Gelman, 2000).

Certain aspects of the magnitude hypothesis have been disputed. It has been suggested that the analog magnitude system is primarily based on activation of the IPS (intraparietal sulcus; Dehaene, Piazza, Pinel & Cohen, 2003); however, neuroimaging studies did not find IPS activation to be specific for the subitizing range (Piazza, Mechelli, Butterworth & Price, 2002). In addition, Dehaene and Cohen (1995) suggested that the operation of the analog magnitude system is independent of the number of items presented; hence, RT should not be modulated by the number of items. However, it has been found that RT for estimation is relatively constant, while the subitizing RT increases with the number of items (Akin & Chase, 1978; Mandler & Shebo, 1982; Trick & Pylyshyn, 1993). An alternative hypothesis indicated that subitizing is based on a domain-general visual tracking system dedicated to a small set of objects. Converging new evidence favors the visual tracking hypothesis by indicating that estimation but not subitizing follows Weber's law (Revkin, Piazza, Izard, Cohen & Dehaene, 2008). Moreover, there is a positive relationship between individual subitizing abilities and individual visuo-spatial working memory but not estimation abilities and individual visuo-spatial working memory (Piazza, Fumaro, Chinello & Melcher, 2011), demonstrating that subitizing reflects a domain-general mechanism. Furthermore, two different systems for small and large numerosity estimation were found in young infants and animals (Feigenson, Dehaene & Spelke, 2004). Specifically, while babies and animals can discriminate when the arrays that are compared have a ratio of 0.5, they fail to discriminate when the ratio is 0.75 during the comparison of large numbers of dots. In contrast, in the case of comparison of small quantities (smaller than 4), there is no ratio effect, indicating a dissociation between processing of large and small quantities.

Object enumeration deficits among those with DD

Those with DD have difficulties in enumeration tasks, including counting (e.g. Geary, Bow-Thomas & Yao, 1992; Geary, Hoard & Hamson, 1999; Landerl, Bevan & Butterworth, 2004), estimation of large sets of objects (Mazzocco, Feigenson & Halberda, 2011) and subitizing (Moeller, Neuburger, Kaufmann, Landerl & Nuerk, 2009; Schleifer & Landerl, 2011). Specifically, Schleifer and Landerl (2011) compared performance of three groups of DD children (in grades 2, 3, and 4) to matched controls for randomly presented dots in the subitizing and counting ranges. The results indicated that: (1) the subitizing range was 3 dots for the typically developing children and controls; (2) DD groups presented a larger slope in the subitizing range compared to the control groups; and (3) the slope in the counting range was comparable for the two groups. In line with this study, Moeller et al. (2009) compared two children with DD to controls in subitizing and counting. The two DD children had a larger slope in the subitizing range, followed by an increase of saccadic eye movements (indicated by an enlarged number of fixations) in that range. The authors concluded that DD children have to count dots even in the subitizing range. Similarly, a smaller subitizing range was observed in those with genetic arithmetical disabilities (i.e. Turner syndrome; TS) (Bruandet, Molko, Cohen & Dehaene, 2004) and acquired arithmetical dyscalculia (Ashkenazi, Henik, Ifergane & Shelef, 2008).

Subitizing as pattern identification

Recently, Piazza and colleagues (Piazza et al., 2011) discussed subitizing as a reflection of visuo-spatial object individuation capacity. Earlier, Mandler and Shebo (1982) discussed visual mechanisms underlying subitizing; specifically, they suggested that the spatial arrangements of 1 to 4 dots always create a familiar shape – a line between two dots, a triangle of three dots, and a quadrilateral form for four dots. Therefore, subitizing quantities are recognized by their familiar shapes. This mechanism plays a major role in the initial stage of counting where a semantic link is created between a ‘number word’ and a spatial configuration (von Gludersfeld, 1982). Accordingly, when a set of dots in the counting range is presented in a familiar shape (i.e. canonical), performance will be similar to that of the subitizing range (i.e. a subitizing-like pattern). Support for this claim was found in a few studies (Buckley & Gillman, 1974; Fink, Marshall, Gurd, Weiss, Zafiris,
The current study

The pattern recognition hypothesis predicts that DD children will have smaller subitizing ranges than control children, and that they will benefit less from canonical displays in the small estimation range. This hypothesis will be tested in the present study. Most of the previous studies that examined DD participants’ enumeration abilities did not manipulate the display (i.e. canonical vs. random). The present study used short exposures and manipulated display characteristics. This will enable us to examine whether subitizing and subitizing difficulties might involve pattern recognition. We will present dots ranging from 1 to 9, for a short presentation time, and ask participants to name the dots: (1) in the subitizing range (1–4 dots), or (2) in the small estimation range (5–9 dots).

We expect DD participants to have a smaller subitizing range than the controls. The question whether the DD group will present difficulties in the small estimation range with the canonically presented dots remains open. Converging new evidence indicates that subitizing is based on a visuo-spatial domain-general mechanism, which possibly involves pattern recognition. Thus, subitizing is dissociable from a number sense or estimation (Piazza et al., 2011). In line with this view, if DD is purely a domain-specific number sense disorder, and subitizing reflects a domain-general ability, then DD participants should present intact subitizing and subitizing-like (canonical arrangement) abilities.

However, new evidence indicates that those with DD have domain-general deficits in visuo-spatial working memory tasks (Rotzer et al., 2009; Ashkenazi, Rosenberg-Lee, Tenison & Menon, 2012). Thus, subitizing and subitizing-like (canonical arrangement) deficits among those with DD potentially reflect visuo-spatial working memory weakness (Rotzer et al., 2009).

Method

Participants

Twenty-two children were selected from 600 3rd or 4th grade children in five municipal elementary schools in Beer-Sheva, Israel. Eleven were diagnosed with DD, and 11 controls had no learning disabilities.

DD group

The mean age of the DD group was 114.1 months with an SD of 7.2. The DD group comprised two males and nine females. Our arithmetical battery for DD was based on the Israeli Ministry of Education curriculum (for more details, see Ashkenazi, Mark-Zigdon & Henik, 2009a).

Children were recruited as follows: First, we asked the teachers to report children with major difficulties in arithmetic but with average or above-average class achievements in all other areas. The teachers suggested 30 students. From this group we selected a sub-group that was diagnosed as having DD according to our arithmetical battery, and that had never been diagnosed as having other developmental learning disabilities such as dyslexia, dysgraphia, or ADHD. All participants were diagnosed before the beginning of this study by using an arithmetical battery that was based on the Israeli Ministry of Education curriculum. Hence, the requirements were different for the different grade levels – different operations for every class level were created to reflect these requirements (e.g. children were asked to count aloud from 7 up to 15 at the 1st grade level, from 326 up to 334 at the 2nd grade level, from 4493 up to 4503 at the 3rd grade level, and from 9996 up to 10,004 at the 4th grade level). Specifically, every child was tested with stimuli that matched his or her current class level, one grade below the current class level and two grades below the current class level. The arithmetical battery for children in the 3rd grade included three kinds of operation: operations that children were expected to master at the 1st grade level, at the 2nd grade level, and at the 3rd grade level. For children in the 4th grade, there were also three different levels of operation: operations expected to be mastered by children at the 2nd grade level, at the 3rd grade level, and at the 4th grade level. We examined accuracy for every subtest (for the individual subtests and examples see Table 1).

Participants with scores appropriate for two grades below their chronological age in most of the subtests of this test were defined as having DD. Specifically, to be selected for the DD group, a child needed to be less than 50% accurate at the current grade level and one level below the current level. For example, if a child in the 3rd grade had less than 50% accuracy in operations at the 3rd and 2nd grade level, he was defined as having DD.
Reading abilities were tested with the Hebrew version of the DST – Dyslexia Screening Test (Fawcett & Nicolson, 2004). The subtests included word naming, word reading, phonological discrimination, word dictation, reading pseudowords, and reading texts adapted to the participant’s age. All of the subtests were based on Israeli reading norms for the appropriate age group. Our DD sample did not have any reading problems and were in the normal range (between 25% and 75% of the normal population) for this test (see Table 2 for the full details of the reading and IQ task).

Control group

The mean age of the control group was 113.8 months with a SD of 7.7 months. The group comprised two males and nine females, selected according to their teacher’s assessment. We asked the teachers for children in the 3rd and 4th grade that had average class achievement in all subjects, including math. Individual controls were age, gender, and class (i.e. same learning class) matched with the individual DD children. Control

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children took the arithmetic, reading, and Raven’s Progressive Matrices tests. None of them exhibited any learning disability. Their achievements were average or above average (see Table 1 and Table 2 for details).

Apparatus
The experiment was run on an IBM R50e laptop. The experiment was programmed using E-Prime.

Stimuli and procedure
In each trial, participants were presented with a group of dots at the center of a screen. They were asked to say aloud the number of dots that was 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 dice; see Figure 1). The dots were presented in a light green color on a black background.

The number of dots varied between 1 and 9. Vocal RTs and errors were recorded. Vocal RTs were input via a microphone and were recorded electronically by a response box controlled by E-Prime software. RT was measured from onset of the stimulus to onset of the vocal response.

A typical trial started with a fixation asterisk for 300 ms, followed by a blank screen for 500 ms, a stimulus for 200 ms, and a blank screen until the experimenter keyed in the participant’s response. The inter-trial interval (from the experimenter’s key-press to the onset of fixation of the next trial) was 1500 ms. There were 288 trials in two blocks (i.e. 144 trials per block: 2 arrangements (canonical, random) × 9 quantities × 8 repetitions). The canonical and random displays were intermixed randomly.

Results
Subitizing and small estimation: accuracy analysis
As was made clear in the introduction, it is common to analyze subitizing and counting data separately. As such, in what follows we will present different analyses for RTs and accuracy for each range.

Table 2  IQ and reading: subtest, testing method, and error rates of controls and DD participants

<table>
<thead>
<tr>
<th>Subtest</th>
<th>Content and example of item</th>
<th>Control percentile</th>
<th>DD percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>IQ</td>
<td>Raven test</td>
<td>60.4 (26.28)%</td>
<td>58.45 (20.08)%</td>
</tr>
<tr>
<td>Rapid naming</td>
<td>Name figures as fast as you can</td>
<td>40.5 (28.9)%</td>
<td>25.3 (23.7)%</td>
</tr>
<tr>
<td>Reading</td>
<td>Read as many words as you can in a minute</td>
<td>84.5 (22%)</td>
<td>85 (14%)</td>
</tr>
<tr>
<td>Phonological awareness</td>
<td>Decompose words</td>
<td>82.5 (16.12%)</td>
<td>67.33 (30.66%)</td>
</tr>
<tr>
<td>Spelling</td>
<td>Write dictated words</td>
<td>51.68 (32.3%)</td>
<td>38.88 (29.65%)</td>
</tr>
<tr>
<td>Digit span</td>
<td>Remember digits backwards</td>
<td>80.37 (21.89%)</td>
<td>72.22 (21.08%)</td>
</tr>
<tr>
<td>Copying</td>
<td>Copy a short paragraph in one minute</td>
<td>48.12 (30.2%)</td>
<td>39.33 (25.5%)</td>
</tr>
<tr>
<td>Verbal fluency</td>
<td>Give words that start with specific letters</td>
<td>39.75 (23%)</td>
<td>32.89 (28%)</td>
</tr>
<tr>
<td>Semantic fluency</td>
<td>State words from a specific category</td>
<td>44 (15.4%)</td>
<td>30.6 (14.1%)</td>
</tr>
<tr>
<td>General reading abilities</td>
<td>DST: Dyslexia Screening Test</td>
<td>59.01 (15.4%)</td>
<td>48.48 (14.13%)</td>
</tr>
</tbody>
</table>

Note: Standard deviations are in parentheses.
conditions, \( F(1, 20) = 16.65, \text{MSE} = 0.001, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(1, 20) = 8.79, \text{MSE} = 0.19, p < .01 \). Moreover, the accuracy decreased as the number of dots increased, \( F(4, 80) = 14.1, \text{MSE} = 0.02, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(4, 80) = 10.21, \text{MSE} = 0.01, p < .01 \), resulting in a significant linear trend, \( F(1, 20) = 14.92, \text{MSE} = 0.04, p < .01 \). However, the quadratic trend was also significant, \( F(1, 20) = 45.85, \text{MSE} = 0.04, p < .01 \). The cubic and the order 4 trend were non-significant (minimum \( p = .09 \)). The linear trend stayed significant after an arcsine transformation, \( F(1, 20) = 10.21, \text{MSE} = 0.09, p < .01 \). Similarly, the quadratic trend stayed significant after an arcsine transformation, \( F(1, 20) = 34.45, \text{MSE} = 0.04, p < .01 \). Moreover, participants were more accurate for the canonical arrangement (0.90, \( SD = 0.12 \)) compared to the random arrangement (0.64, \( SD = 0.17 \)), \( F(1, 20) = 128.9, \text{MSE} = 0.03, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(1, 20) = 168.4, \text{MSE} = 0.05, p < .01 \). In addition, arrangement and quantity interacted, \( F(4, 80) = 10.3, \text{MSE} = 0.015, p < .05 \). The difference between the canonical and the random arrangement was larger in the 6-, 7-, 8-, and 9-dots conditions compared to the 5-dots condition, \( F(1, 20) = 78.4, \text{MSE} = 0.004, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(4, 80) = 6.58, \text{MSE} = 0.04, p < .05 \). Importantly, quantity and group interacted, \( F(4, 80) = 2.98, \text{MSE} = 0.02, p < .05 \). The difference between the groups was greater with the large quantities (7, 8, 9 dots) than with the small quantities (5, 6 dots), \( F(1, 20) = 6.5, \text{MSE} = 0.03, p < .05 \). This effect became marginally significant after an arcsine transformation, \( F(4, 80) = 2.29, \text{MSE} = 0.05, p = .08 \). The triple interaction between quantity, group and arrangement was not significant. Nevertheless, because of theoretical importance (i.e. do canonical arrangements produce subitizing-like patterns of performance in each group?), we examined the canonical and random arrangements separately in the two groups;

Small estimation range

Accuracy results were submitted to an ANOVA with three independent variables: quantity of presented dots (5–9) and arrangement of dots (random or canonical) as within participant variables, and group (DD or control) as a between participants variable. Similar to the results in the subitizing range, the three main effects were significant, with DD participants being less accurate (0.71, \( SD = 0.19 \)) than controls (0.830, \( SD = 0.10 \)), \( F(1, 20) = 7.4, \text{MSE} = 0.11, p < .05 \). This effect stayed significant after an arcsine transformation, \( F(1, 20) = 8.79, \text{MSE} = 0.19, p < .01 \). Moreover, the accuracy decreased as the number of dots increased, \( F(4, 80) = 14.1, \text{MSE} = 0.02, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(4, 80) = 10.21, \text{MSE} = 0.01, p < .01 \), resulting in a significant linear trend, \( F(1, 20) = 14.92, \text{MSE} = 0.04, p < .01 \). However, the quadratic trend was also significant, \( F(1, 20) = 45.85, \text{MSE} = 0.04, p < .01 \). The cubic and the order 4 trend were non-significant (minimum \( p = .09 \)). The linear trend stayed significant after an arcsine transformation, \( F(1, 20) = 10.21, \text{MSE} = 0.09, p < .01 \). Similarly, the quadratic trend stayed significant after an arcsine transformation, \( F(1, 20) = 34.45, \text{MSE} = 0.04, p < .01 \). Moreover, participants were more accurate for the canonical arrangement (0.90, \( SD = 0.12 \)) compared to the random arrangement (0.64, \( SD = 0.17 \)), \( F(1, 20) = 128.9, \text{MSE} = 0.03, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(1, 20) = 168.4, \text{MSE} = 0.05, p < .01 \). In addition, arrangement and quantity interacted, \( F(4, 80) = 10.3, \text{MSE} = 0.015, p < .05 \). The difference between the canonical and the random arrangement was larger in the 6-, 7-, 8-, and 9-dots conditions compared to the 5-dots condition, \( F(1, 20) = 78.4, \text{MSE} = 0.004, p < .01 \). This effect stayed significant after an arcsine transformation, \( F(4, 80) = 6.58, \text{MSE} = 0.04, p < .05 \). Importantly, quantity and group interacted, \( F(4, 80) = 2.98, \text{MSE} = 0.02, p < .05 \). The difference between the groups was greater with the large quantities (7, 8, 9 dots) than with the small quantities (5, 6 dots), \( F(1, 20) = 6.5, \text{MSE} = 0.03, p < .05 \). This effect became marginally significant after an arcsine transformation, \( F(4, 80) = 2.29, \text{MSE} = 0.05, p = .08 \). The triple interaction between quantity, group and arrangement was not significant.

![Figure 1](https://example.com/figure1.png)  
**Figure 1**  
Canonical (A) vs. random (B) arrangement for the presentation of 6 dots. (C) Canonical arrangements of 1–9 dots as they appeared in the experiment.

![Figure 2](https://example.com/figure2.png)  
**Figure 2**  
Mean accuracy by range (A. subitizing, B. counting), group, arrangement and the presented quantity of dots.
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Subitizing and small estimation: reaction time analysis

Subitizing range

The RTs of the correct trials were submitted to an ANOVA with three independent variables: quantity of presented dots (1–4) and arrangement of dots (random or canonical) as within participant variables, and group (DD or control) as a between participants variable. There was a main effect for quantity, F(3, 60) = 12.12, MSE = 60,225, p < .01; the RTs increased with increasing quantity, indicated by a significant linear trend, F(1, 20) = 57.64, MSE = 36,421, p < .01. Note that the quadratic and cubic trends were non-significant (minimum p = .36). Moreover, a main effect for arrangement was found, F(1, 20) = 26.2, MSE = 40,322, p < .01, with participants responding slower in the random arrangement condition (809 ms, SD = 289) compared to the canonical arrangement (654 ms, SD = 205) condition. Arrangement and quantity interacted, F(3, 60) = 13.6, MSE = 22,542, p < .01. The difference between the canonical and random arrangement was larger in the 4-dots condition compared to the 1-, 2- and 3-dots conditions, F(1, 20) = 51.8, MSE = 17,827, p < .01. Importantly, quantity and group interacted, F(3, 60) = 3.4, MSE = 60,225, p < .05. The mean slope of the control group (−17 ms, SD = 30.07) was smaller than the slope of the DD group (147 ms, SD = 149.77), t(20) = 2.17, p < .05. No other effects (including group effect) were significant (see Figure 3).

Small estimation range

The RTs of the correct trials were submitted to an ANOVA with three independent variables: quantity of presented dots (5–9) and arrangement of dots (random or canonical) as within participant variables, and group (DD or control) as a between participants variable. The effect of arrangement was significant, F(1, 20) = 136, MSE = 195,600, p < .01, with participants being slower to respond in the random arrangement (3000 ms, SD = 929) compared to the canonical arrangement (1649 ms, SD = 639). The effect of quantity was also significant, F(4, 80) = 41.19, MSE = 1,950,900, p < .01, with participants being slower as the quantity of dots increased, indicated by a significant linear trend, F(1, 20) = 73.19, MSE = 105,630, p < .01. Note that quadratic, cubic, or order 4 trends were not significant (minimum p = .11). Arrangement, quantity, and group interacted, F(4, 80) = 4.6, MSE = 1,205,361, p < .01. In the control group, the difference between the random and canonical conditions became larger as the quantity of the dots increased, F(1, 20) = 7.1, MSE = 479,214, p < .05, whereas in the DD group (similar to the error rate results) the difference between the canonical and the random conditions was not modulated by the quantity (ns) (see Figure 3). No other effects (including group effect) were significant.

Coefficient of variation (CV) analysis

According to Gallistel and Gelman (2000), the variability of responses should increase as the size of the number increases. Accordingly, the relation between the standard deviation and the mean estimation of the presented dots should be fixed throughout the range. We examined this separately for the two ranges and excluded the quantity 9 in order to avoid an end effect. For each participant in each condition we computed CV – standard deviation divided by mean estimation.

Figure 3 Mean RTs by range (A. subitizing, B. counting), group, arrangement and the presented quantity of dots.
The CVs were submitted to an ANOVA with three independent variables: quantity of presented dots (1–4) and arrangement of dots (random or canonical) as within participant variables, and group (DD or control) as a between participants variable. There was a main effect for arrangement, $F(1, 19) = 9.982$, $MSE = 0.05$, $p < .01$; the CV was larger in the random arrangement (0.06) compared to the canonical arrangements (0.02). CV was not modulated by quantity. No other effects (including group effect) were significant (see Figure 4).

**Figure 4** Coefficient of variation: deviation of standard deviation by the mean estimation. (A) Coefficient of variation as a function of group and arrangement. (B) Relation between mean estimation and standard deviation for the individual control subjects. (C) Relation between mean estimation and standard deviation for the individual DD subjects.

Subitizing range

The CVs were submitted to an ANOVA with three independent variables: quantity of presented dots (5–8) and arrangement of dots (random or canonical) as within participant variables, and group (DD or control) as a between participants variable. First, the effect of group was significant, $F(1, 18) = 12.99$, $MSE = 0.02$, $p < .01$. The CV was larger in the DD group (0.07) compared to the control group (0.05). The effect of arrangement was significant, $F(1, 18) = 139.59$, $MSE = 0.11$, $p < .01$, with the CV of the random

Small estimation range
arrangement (0.08) larger than the CV of the canonical arrangement (0.03). The effect of quantity (contrary to the prediction) was also significant, \( F(3, 54) = 11.52, \text{MSE} = 0.0076, p < .01 \); however, the trend was not linear (\( F < 1 \)) but quadratic (see Figure 4). No other effects were significant. Figures 4B and 4C represent the individual relationships between the mean estimation and standard deviation of the presented dots for the canonical and random arrangements. As can be seen in the figure, similar to our previous results in the small estimation range, most of the control participants presented a smaller slope in the canonical arrangements compared to the random arrangements. However, most of the DD participants presented a similar slope in the two ranges.

**Discussion**

Let us summarize the main results: (1) DD participants showed a decreased subitizing range as indicated by accuracy and RT. (2) In the small estimation range, DD participants were less accurate and slower than controls. Moreover, the increase in errors and RT as a function of quantity was larger for the DD group than for controls. (3) Differences between random and canonical arrangements were observed in most of the conditions. Participants in the two groups were slower to respond and made more errors in the random arrangement compared with the canonical arrangement. In addition, in the canonical arrangement, the control group presented a subitizing-like pattern for the small estimation range. Namely, accuracy was not influenced by the quantity of the dots, and the slope of the RT was smaller for the canonical arrangement compared to the random arrangement. DD participants presented limited benefits from the canonical presentation; in general (as a main effect), they presented reduced error rates and faster RTs in the canonical arrangement compared to the random arrangement. However, DD participants did not present a subitizing-like pattern in the small estimation range; thus, as the quantity of the dots increased, the error rate increased and the slope of RT was not modulated by arrangement. Importantly, DD participants presented deficits in canonical arrangements of dots in the subitizing and small estimation range, indicating that they had difficulties in implicit pattern recognition. (4) The CV was affected by the arrangement in the two ranges. It was not modulated by the quantity of dots in the subitizing range but was affected by it in the small estimation range (note that it was not linear). (5) The CV was larger in the DD group compared to the controls in the small estimation range but not in the subitizing range.

The present study was aimed at examining enumeration abilities in those with DD. A wide range of studies
have already examined enumeration abilities among those with DD and found deficits in subitizing and counting (e.g. Koontz & Berch, 1996; Moeller et al., 2009; Schleifer & Landerl, 2011; Van der Sluis, De Jong & van der Leij, 2004). However, previous studies did not manipulate pattern recognition. Accordingly, we presented dots in both canonical and random arrangements. As in previous studies, deficits were discovered among those with DD in both subitizing and small estimation (Geary et al., 1992; Geary et al., 1999; Landerl et al., 2004; Moeller et al., 2009; Schleifer & Landerl, 2011). Importantly, deficits among those with DD were discovered in the canonical arrangement condition, which hints at a subitizing deficit in DD involving pattern recognition deficits.

Mandler and Shebo (1982) suggested that the spatial arrangement of dots in the subitizing range always creates a recognizable pattern (e.g. a line for 2 dots, a triangle for 3 dots). Processing of such patterns involves a pattern recognition system, which contributes to efficient and fast processing. Dehaene and Cohen (1994) suggested that this pattern recognition system is also exploited in processing of canonical stimuli (see also Piazza, Giacomini, Le Bihan & Dehaene, 2003). Hence, it is possible that the deficit in the DD participants in processing canonical arrangements may be due to difficulties in pattern recognition. Moreover, it is possible that the deficit in processing stimuli in the subitizing range in the DD participants may be related to this difficulty.

It has been suggested that those with DD, but not matched controls, perform saccadic eye movements in the subitizing range (Moeller et al., 2009). Combining this result with the current results suggests that those with DD have difficulties in recognizing the pattern of the display due to multiple eye movements.

Pattern recognition difficulties among DD participants can be based on domain-general visuo-spatial working memory deficits (Rotzer et al., 2009) or domain-specific rapid enumeration deficits. Lately, it has been suggested that subitizing abilities reflect domain-general visuo-spatial working memory abilities (Piazza et al., 2011; Revkin et al., 2008) rather than domain-specific number enumeration abilities. Similarly, in the subitizing range, the visual short-term memory range is limited to 3 to 4 items and the activity level of the IPS increases with the increase in the number of presented items (Todd & Marois, 2004; Vogel & Machizawa, 2004). Specifically, in a study that examined brief presentations of a set of colored dots and a delayed presentation of a single color target dot, the participants had to determine whether the color of the target dot matched the color of the dots in the same location in the original set. The level of activity in the IPS increased with the size of the set of dots until a limit of 3 or 4 dots, where the activity level reached plateau (Todd & Marois, 2004; Vogel & Machizawa, 2004). Interestingly, the individual subitizing range was strongly correlated to the individual range of visual short-term memory or visuo-spatial working memory (Piazza et al., 2011) but not to domain-specific number comparison abilities. Pattern identification requires an intact ability of visual and spatial working memory, where the representation of familiar patterns is kept. In line with this hypothesis, participants that were diagnosed with cerebral palsy had a lower subitizing range compared to matched control. Specifically, cerebral palsy participants did not benefit from the condition of a canonical presentation compared to a random arrangement. Moreover, cerebral palsy participants had difficulty in pattern recognition and difficulties in visuo-spatial short-term memory. To sum up, a recent theory (Piazza et al., 2011) suggests that subitizing involves individual domain-general visual short-term memory capacities. Visual short-term memory is needed in the case of pattern recognition. Accordingly, weakness in pattern recognition and subitizing among those with DD can indicate that: (1) Subitizing involves a domain-general process that is related to pattern recognition, or is based on similar cognitive mechanisms such as pattern recognition (i.e. visual short-term memory). (2) This domain-general weakness adds to the domain-specific weakness among those with DD.

In line with this hypothesis, domain-general visuo-spatial working memory deficits were found among those with DD (Rotzer et al., 2009). Specifically, Rotzer et al. (2009) compared brain activity during a visuo-spatial task in a group of 8–10-year-old DD children with a group of controls. The results indicated that participants suffering from DD had an under-activated right inferior frontal gyrus, right IPS, and right insula during the visuo-spatial working memory task. Moreover, the individual level of activity in the right IPS and insula were positively correlated to out-of-scanner measurements of visuo-spatial working memory. Note that the DD group, compared to the control group, had a significantly lower verbal IQ, verbal working memory abilities, and visuo-spatial abilities. Importantly, an indication for inferior visuo-spatial working memory abilities was found in a group of children with DD compared to a control group that was matched according to IQ and verbal working memory abilities (Ashkenazi et al., 2012). The preceding discussion has dealt with subitizing deficits in those with DD; the next section will discuss weakness in the small estimation range for this population.

Those with DD have a specific difficulty in number processing (e.g. Geary & Hoard, 2001; Ginsburg, 1997; Koontz & Berch, 1996; Rubenstein & Henik, 2005, 2006; Russell & Ginsburg, 1984). In addition, neuro-anatomical studies have found abnormal structures or activity in those with DD in brain areas involved in counting (Cohen Kadosh et al., 2007; Kaufmann, Vogel, Starke, Kremser & Schocke, 2009; Molko et al., 2003; Price et al., 2007). Hence, it comes as no surprise that those with DD have difficulties in small estimation or the counting range. However, a study that examined counting in DD
participants and presented dots in the range of 4–9 discovered intact abilities in the counting range (Schleifer & Landerl, 2011). Note that in the present study, the stimuli were presented briefly compared to the unlimited presentation time in Schleifer and Landerl’s (2011) study.

It has been suggested that the deficit in DD involves the IPS (Cohen Kadosh et al., 2007; Isaacs et al., 2001; Molko et al., 2003; Price et al., 2007). The IPS was found to be activated during number processing (Arsalidou & Taylor, 2011; Cohen Kadosh, Lammertyn & Izard, 2008). However, the IPS is also strongly involved in visual processes such as visual short-term memory (Todd & Marois, 2004). Accordingly, abnormal IPS activity in DD can lead to subitizing deficits in addition to numerical processing deficits. To sum up, abnormal IPS activity can be the basis of the weakness in number processing, pattern recognition, and subitizing in those with DD. Note, however, that DD participants in the current study did not present difficulties in the Raven test with DD. Note, however, that DD participants in the current study did not present difficulties in the Raven test.

To summarize, the result of a similar deficit in canonical counting and subitizing in DD participants can hint that the two processes are partly based on the same cognitive mechanism, that is, pattern recognition. In future studies it will be interesting to evaluate the saccadic eye movements of those with DD during enumeration of canonical arrangements of dots.

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References


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