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Numerical estimation in adults with and without developmental dyscalculia

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ABSTRACT

It has been hypothesized that developmental dyscalculia (DD) is either due to a defect of the approximate number system (ANS) or to an impaired access between that system and symbolic numbers. Several studies have tested these two hypotheses in children with DD but none has dealt with adults who had experienced DD as children.

This study aimed to compare these two hypotheses in an adult population in order to investigate which deficits still persist at that age. To that aim, numerical estimation tasks were given to adults who had or had not experienced DD as a child. Three of the estimation tasks required a mapping between the ANS and symbolic numbers: participants had to estimate the number of same or different-sized dots presented by producing the corresponding Arabic number or, conversely, to produce the number of dots corresponding to a presented Arabic number. A fourth task did not require any processing of symbolic numbers; participants had to produce a collection of dots of the same numerosity as another one previously presented.

Consistently, in all the four numerical tasks and irrespective of whether the tasks used symbolic numbers or not, the estimates of DD participants were less accurate than those of the control participants. These results indicate that adults who had experienced DD as children continue to demonstrate a less precise magnitude representation.

1. Introduction

Developmental dyscalculia (DD) refers to a specific learning disability affecting the acquisition of arithmetic skills and numerical competences, despite normal intelligence and in the absence of neurological injuries (Temple, 1992). Epidemiological studies have indicated that DD affects between 3.5% and 6.5% of the school-age population (GrossTsur, Manor, & Shalev, 1996; von Aster & Shalev, 2007) and often persists into late adolescence (Shalev, Manor, & Gross-Tsur, 2005).

Two main hypotheses have been put forward to explain DD. According to the first one (Berch, 2005; Spelke & Kinzler, 2007; Wilson & Dehaene, 2007), difficulties in symbolic mathematics originate from a specific deficit in the innate ability to represent and manipulate numerical quantities which is supported by the analog and approximate number system (ANS; Dehaene, 1997, but see Butterworth, 2005 for an exact perspective of magnitude representation). We will thus call it the ANS deficit hypothesis. Conversely, according to the access deficit hypothesis (Rousselle & Noël, 2007), DD arises from problems in accessing an intact magnitude representation from symbolic numbers (e.g., Arabic numbers or number words).

Currently, the locus of impairment remains uncertain as evidence in support of both hypotheses has been reported. Moreover, no study specifies the longevity of numerical impairment in adults with DD. This study aims to compare the predictions of these two hypotheses in an adult population suffering from DD.

1.1. Comparing the two hypotheses

The ANS deficit hypothesis received support from studies showing impairment in tasks requiring the processing of number magnitude, including those using only non-symbolic material (e.g., dot collections). For instance, it has been shown that DD children of 11–12 years of age committed more errors than did controls in a numerical comparison of small sets (Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007). Similarly, Mussolin, Mejias, and Noël (2010) showed that 10–11-year-old DD children showed longer latencies and higher error rates than control children in both symbolic and non-symbolic comparison tasks on small and close numerosities. Consistently, investigating 8–12 year-olds, Piazza et al. (2010) showed that DD children had a lower acuity than control children when comparing the magnitude of two large numerosities. Finally, in an unselected population, math performance recorded from kindergarten to grade six was significantly correlated with the acuity of the ANS measured at 14 years old by a number magnitude comparison task of dot collections (Halberda, Mazzocco, & Feigenson, 2008). All these studies show that low math achievement

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and DD are associated with lower acuity of the ANS and thus support the ANS deficit hypothesis.

However, other studies testing younger DD children support the access deficit hypothesis as they showed normal performance of DD children in numerical tasks using non-symbolic stimuli but impaired performance in tasks using symbolic stimuli. In particular, De Smedt and Gilmore (2011) found that 6–7-year-olds with DD performed worse than controls in comparing Arabic numbers (AN) but not in comparing non-symbolic numerosities (sets of dots). The same results were initially found by Rousselle and Noël (2007) in 7–8-year-old DD children. Testing children in the same age-range, Iuculano, Tang, Hall, and Butterworth (2008) also showed that low-numeracy children performed within the normal range in approximation tasks using non-symbolic material but exhibited poorer results than control children in tasks using AN. Finally, in unselected population of 6-year-olds, math achievement was seen to correlate with performance in an AN comparison task but not in a non-symbolic magnitude comparison task (Holloway & Ansari, 2009). Those results support the access deficit hypothesis: the ANS would be intact but an impaired access to the ANS from symbols would lead to DD.

Thus, very different profiles are observed in younger versus older children with DD. Noël and Rousselle (in press) have proposed a developmental perspective that integrates these differences. According to these authors, the initial difficulty of DD children lies in processing the meaning of symbolic numbers and mapping them onto the ANS (i.e., the access deficit hypothesis). Secondly, the use of symbolic numbers in exact calculation would lead to an increase in precision of the ANS. However, such a refinement would be much less pronounced in DD children since they encounter many difficulties in processing and operating on exact numbers. Accordingly, after a few years of schooling, the lack of refinement of the ANS in DD children would lead to a significantly lower acuity of that representation in DD relative to control children. However, no one knows whether this lack of refinement of the ANS is permanent or corresponds to a developmental delay that would, for instance, no longer appear in adulthood.

Some longitudinal studies show that DD is a long-lasting problem (e.g., Shalev et al., 2005) but only a few studies have tried to examine the basic deficit that might underlie these mathematical difficulties in adulthood. To our knowledge, the only studies that have gone in this direction are those of Henik's team (Ashkenazi, Rubinsten, & Henik, 2009; Rubinsten & Henik, 2005). Using a numerical Stroop task, they have shown that, unlike control adults, DD participants did not seem to automatically activate the number magnitude of AN. They concluded that adults with DD have impaired access to magnitude representation from AN. However, as the processing of non-symbolic information was not investigated, it leaves open the question of an ANS deficit in DD adults rather than an access deficit to that representation from symbols.

1.2. Measuring the ANS by numerical estimation tasks

To date, no study has investigated which deficits still persist in DD adults. We do not know if the poor abilities of DD children in basic numerical tasks reflect a developmental delay which recovers later on, or corresponds to a long-lasting deficit that is still present in adulthood. Extending the previous studies conducted on children, we want to explore whether the weak acuity of the ANS present in older children is still present in adults or whether they only show difficulties in tasks using number symbols. By comparing DD and control participants' performance in numerical estimation tasks contrasting the use of symbolic and non-symbolic numbers, we will compare the ANS deficit and the access deficit hypotheses. Indeed, numerical estimation tasks provide a direct assessment of the ANS (Dehaene, 1997; Dehaene & Cohen, 1991, 1997; Stanescu-Cosson et al., 2000). Such a representation is approximate: it is noisy as the mean and standard deviations of participants' estimations increase in proportion to the target magnitudes, thus leading to a constant coefficient of variation (COV = standard deviation of mean response/mean response) across target magnitudes (Cordes, Gelman, Gallistel, & Whalen, 2001).

Accordingly, four estimation tasks were presented to DD and control adult participants. In the first task, collections of same-sized dots were presented to the participants, who had to estimate their numerosity by producing an AN. The same task performed in reverse was also used, as Mundy and Gilmore (2009) showed that children were less precise when asked to select a dot collection corresponding to an Arabic number than vice versa. However, since the dots were of equal size, the estimate could have been influenced by the total surface area covered by the dots (Rousselle, Palmers, & Noël, 2004). Accordingly, a heterogeneous sized dots condition was also used in which collections of different sized dots were made, leading to a constant cumulative surface area across numerosities. Again, participants had to produce the AN corresponding to the cardinality of the collection. Finally, a completely non-symbolic task was used in which participants were presented with heterogeneous-sized dot collections and had to produce a collection of the same numerosity but with homogeneous-sized dots. According to the ANS deficit hypothesis, DD participants should show lower performance in all these numerical estimation tasks since they all involve the ANS. Conversely, the access deficit hypothesis predicts a deficit in the first three but not the last task. As only the first three involve a mapping between the ANS and numerical symbols.

2. Method

2.1. Participants

A total of 44 Caucasian adults took part in the experiment: 22 of them were identified as having DD in their childhood and 22 were classified as controls (C). The two groups of adults did not differ in terms of gender (6 males and 16 females in each group) or age (see Table 1).

2.1.1. Participant selection procedure and classification scheme

Participants were recruited via an advertisement saying that we were looking for (a) individuals who had had significant difficulties in learning mathematics during childhood and/or who had been diagnosed as “dyscalculic”; (b) individuals who had never had specific learning difficulties. Then both groups responded to a questionnaire and were included in a group if they fulfilled the particular criteria (see Appendix A for details of the recruitment and matching procedures).

2.2. Experimental tasks

2.2.1. Assessments of arithmetical performance and memory span for visual patterns

After we ran the experiment, and in order to confirm that arithmetical difficulties persist into adulthood, participants went through a battery of arithmetical tests which are part of the standardized battery developed by Shalev et al. (2001) and adapted by Rubinsten and Henik (2005, see Appendix B).

Moreover, as our experiment assumed good visuo-spatial abilities, participants went through an assessment of their memory span for visual patterns. This task, a paper and pencil version of that developed by Wilson, Scott, and Power (1987), involved the presentation of matrices in which some cells were randomly completed; the participants had to recall which cells had been filled in. The complexity increased every time the participant was successful in two out of three attempts. Participants made their responses in a booklet of blank matrices, corresponding in size to the target patterns to be recalled. The initial level of complexity involved filling in two cells.