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Numerical estimation in individuals with Down syndrome

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ABSTRACT

We investigated numerical estimation in children with Down syndrome (DS) in order to assess whether their pattern of performance is tied to experience (age), overall cognitive level, or specifically impaired. Siegler and Opfer's (2003) number to position task, which requires translating a number into a spatial position on a number line, was administered to a group of 21 children with DS and to two control groups of typically developing children (TD), matched for mental and chronological age. Results suggest that numerical estimation and the developmental transition between logarithm and linear patterns of estimates in children with DS is more similar to that of children with the same mental age than to children with the same chronological age. Moreover linearity was related to the cognitive level in DS while in TD children it was related to the experience level.

1. Introduction

Down syndrome (DS) is caused by abnormalities of chromosome 21, and affects about 1 in 1000 live births (McGrowther & Marshall, 1990). The great majority of individuals with DS have mild to severe levels of intellectual impairment and a wide range of associated physical, medical, and cognitive deficits (e.g., Silverman, 2007). Previous research has shown specific deficits in language, while visuo-spatial abilities are relatively preserved (e.g., Dykens, Hodapp, & Finucane, 2000, for a review). Deficits in working memory (Lanfranchi, Baddeley, Gathercole, & Vianello, 2012) and executive functions (Lanfranchi, Jerman, Dal Pont, Alberti, & Vianello, 2010) have also been detected. Importantly, several studies have also reported that individuals with DS have difficulties in mathematics (e.g., Gelman & Cohen, 1988; Nye, Fluck, & Buckley, 2001; Porter, 1999). The origin of these difficulties is a debated topic. Some researchers support the *developmental hypothesis* (Zigler, 1969), suggesting that the mathematical difficulties of individuals with DS stem from their low general cognitive level (e.g., Caycho, Gunn, & Siegal, 1991). Others support the *difference hypothesis* (e.g., Gelman & Cohen, 1988; Nye et al., 2001) by showing poorer performance of individuals with DS in comparison to typically developing (TD) children of same mental age (MA). Gelman and Cohen (1988), for example, found that children with DS had lower performance compared to preschoolers matched for MA in both counting and cardinality tests. Similarly, Porter (1999) found that children with DS were unable to detect errors violating counting principles. Nye et al. (2001) reported that children with DS produced fewer words and shorter counting sequences, as well as counted smaller arrays of objects, than typically developing children

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matched for MA. Finally, numerosity discrimination is less efficient in individuals with DS than in MA controls for small numerosities (i.e., within the subitizing range; Paterson, Girelli, Butterworth, & Karmiloff-Smith, 2006; Sella, Lanfranchi, & Zorzi, 2013) but not for larger numerosities (Camos, 2009; Paterson et al., 2006; Sella, Lanfranchi, et al., 2013).

Numerical estimation is a central part of mathematical understanding, requiring integration of conceptual and procedural knowledge of numbers (Siegler, Thompson, & Opfer, 2009). Indeed, numerical estimation is a process of translating between alternative quantitative representations, at least one of which is inexact and at least one of which is numerical (Siegler & Booth, 2005). Numerical estimation tasks have proved particularly useful for providing insights into children's numerical development and their understanding of numerical magnitudes (Siegler & Opfer, 2003; Siegler et al., 2009). A widely used numerical estimation task is Siegler and Opfer's (2003) number-to-position task, which requires translating a number into a spatial position on a ‘‘number line’’. In this task, children are shown a visual line flanked by a number at each end (e.g., 0 and 1000) and they have to indicate where a given number (e.g., 75) would fall on the line. This estimation task is particularly revealing about the mapping of numerical magnitude because it transparently reflects the ratio characteristics of the number system. In their seminal study, Siegler and Opfer found that the estimates of numerate adults are linearly related to numerical magnitude, whereas children show a developmental progression from a logarithmic to a linear pattern. That is, the pattern of estimates in younger children is characterized by overestimation of small numbers and underestimation of larger numbers, thereby showing a logarithmic mapping that is thought to reflect the preverbal system of approximate magnitude representation (the Approximate Number System; Feigenson, Dehaene, & Spelke, 2004; Piazza, 2010; Stoianov & Zorzi, 2012). With increasing age and education (in particular, familiarity with the tested numerical range), children shift from this compressed pattern to a formal and linear pattern that entails the accurate placement of numbers (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003).

Note that the nature of the compressed pattern of estimates is debated (e.g., Barth & Paladino, 2011; Karolis, Iuculano, & Butterworth, 2011) and for this reason we refer to the classic distinction between logarithmic and linear positioning without assuming that the selected model is a faithful index of the underlying representation (also see Berteletti, Lucangeli, & Zorzi, 2012). Nevertheless, it is widely accepted that the shift between these two patterns is an indication of an increased understanding of the numerical values and the principles that underline the numerical system.

Numerical estimation is important for a variety of educational outcomes. In particular, it is related to general measures of mathematical proficiency and to measures of specific numerical processes (Booth & Siegler, 2008; Laski & Siegler, 2007), as well as to memory for numbers (Thompson & Siegler, 2010). Moreover, early estimation skills predict later success in mathematics (Chard et al., 2005; Jordan, Kaplan, Nabors Olah, & Locuniak, 2006). Notably, children with mathematical learning disabilities often generate logarithmic patterns of estimates in the number-to-position task when same-age typically developing (TD) children have already shifted to a linear mapping (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Sella, Lucangeli, Zorzi, & Berteletti, 2013). Moreover, lower precision of estimation persists in children with mathematical learning disabilities even when they have achieved a linear mapping, and the discrepancy from TD peers seems to be related to differences in IQ and in working memory (Geary et al., 2008). In this sense the general level of cognitive functioning seems to influence the emergence of an adequate mapping of numerical magnitude.

In the present study we focused on numerical estimation in DS, which, to the best of our knowledge, has never been investigated in previous studies. In particular we assessed numerical estimation in individuals with DS against those of two groups of TD children, one matched for chronological age (TD-CA) and one matched for mental age (TD-MA). The key question is whether the pattern of estimates displayed by individuals with DS – and hence the type of mapping (logarithmic vs linear) deployed in the task – is tied to experience (indexed by chronological age and schooling), overall cognitive level (indexed by mental age) or shows specific deficit even with respect to mental age.

2. Materials and methods

2.1. Participants

Twenty-one pre-teen and teenagers with DS (9 males; M_{age} = 14 years, 2 months) took part in the study. Two control groups of TD individuals were recruited. One group (N = 21, 9 males; M_{age} = 5 years, 6 months) was matched for mental age (TD-MA) to the DS group and it served to provide an indication of typical performance at a given development level. The second group (N = 21, 9 males; M_{age} = 14 years, 2 months) was matched for chronological age (TD-CA) to the DS group and it served to take into account length of experience. None of the participants had associated physical deficits that could compromise the execution of the tasks. All children were Caucasian. Parental consent was obtained prior to testing. All participants were included in a broader study on numerical cognition in DS and a different portion of these data has been reported in Sella, Lanfranchi, et al., 2013. The study was conducted in accordance with the standard ethical guidelines as defined by the Declaration of Helsinki.

Matching for mental age was based on measures of verbal mental age (Peabody Picture Vocabulary Scale-Revised, PPVT-R; Dunn & Dunn, 1997). A TD child was included in the TD-MA control group when his/her raw scores on the PPVT-R fell within (in either direction) 4 standard score points of the corresponding DS child score. A TD child was included in the chronological age group when his/her chronological age was within (in either direction) 4 months of the corresponding DS children age. Moreover, in order to have also a measure of fluid intelligence, the Raven's Coloured Matrices (Raven, Raven, & Court, 1998) were administered to DS and TD-MA groups. The scores of DS and TD-MA groups to both tests are presented in Table 1. A number of studies have used PPVT and Raven Coloured Matrices in order to assess verbal and fluid intelligence in individuals with DS revealing the appropriateness of these tests for this population (e.g., Sella, Lanfranchi, et al., 2013; Lanfranchi et al., 2012).

2.2. Materials

2.2.1. Numerical intelligence

The Numerical Intelligence Scale for children aged from 4 to 6 years (Molin, Poli, & Lucangeli, 2007) provided a measurement of numerical and counting skills. Note that this test is appropriate for our sample of individuals with DS because the average mental age was 5 years. The Numerical Intelligence Scale not only allows establishing a general level of achievement in numerical intelligence, but also provides specific indexes for each area investigated, and specifically Lexical, Semantic, Counting and Pre-syntactical Processes. Lexical tasks assess the knowledge of number names and stable number sequence; semantic tasks assess the abilities to understand the link between numbers and their quantity representations; counting tasks assess the ability to count; pre-syntactical tasks involves spatial relationships among digits, that is understanding their positional value into a multi digit number. The reported test–retest reliability for the Numerical Intelligence Scale is $r = .904$, while the correlations between each task and the total score range between .70 and .95.

2.2.2. Arithmetic knowledge

The assessment of arithmetic knowledge consisted in the following tasks:

1. *Non-verbal calculation*: 4 addition and 4 subtraction problems were presented. In this task, children had to add or subtract one or more dots from a given set. The number of dots for each operand was within the single-digit range.
2. *Story problems*: 4 addition and 4 subtraction single-digit story problems were presented verbally. The child had to respond verbally.
3. *Number facts*: 4 single-digit addition and 4 single-digit subtraction number facts were tested verbally.

A general score of arithmetic knowledge was computed by summing the scores of these three tasks.

2.2.3. Number to position task (Siegler & Opfer, 2003; Berteletti et al., 2010)

In the number-to-position task, children were presented with 25-cm long lines in the centre of white landscape A4 sheets. Two different intervals were administered: 1–10 and 0–100. The ends of the lines were labelled on the left by either 1 or 0 and on the right by either 10 or 100. The number to be positioned was shown in the upper left corner of the sheet. All numbers except for 1, 5 and 10 had to be positioned on the smaller interval (Berteletti et al., 2010), whereas for the larger interval numbers to position were: 2, 3, 4, 6, 18, 25, 48, 67, 71, 86 (corresponding to sets A and B for the same interval used in Siegler & Opfer, 2003). The order of presentation of the two intervals and order of items within each interval were randomized. Each line was presented separately from the previous one. The instructions were: "We will now play a game with number lines. Look at this page, you see there is a line drawn here. I want you to tell me where some numbers are on this line. When you have decided where the number I will tell you has to be, I want you to make a mark with your pencil on this line." To ensure that the child was well aware of the interval size, the experimenter would point to each item on the sheet while repeating for each item: "This line goes from 1 (0) to 10 (100). If here is 1 (0) and here is 10 (100), where would you position 5 (50)?" The experimenter always named the numbers to place. Numbers 5 and 50 were used as practice trials for the small and large interval, respectively. No feedback was given. Experimenters were allowed to rephrase the instructions as many times as needed without making suggestions about where to place the mark.

2.3. Procedure

Participants were recruited through local service centres, associations for families of individuals with DS and local schools in northern Italy. Participants met one on one with the experimenter, an expert in developmental psychology and atypical

Table 1
Group characteristics.

	N	Chronological age		Years of school		Mental age Peabody		Mental age Raven	
		M	SD	*M*	SD	*M*	SD	*M*	SD
DS	21	14 years, 2 months	3 years, 6 months	11 years, 6 months	3 years, 3 months	5 years, 0 months	0 years, 11 months	5 years, 1 months	1 years, 5 months
TD-MA	21	5 years, 6 months	0 years, 10 months	1 years, 3 months	0 years, 7 months	5 years, 2 months	0 years, 10 months	5 years, 6 months	1 years, 2 months
TD-CA	21	14 years, 2 months	3 years, 6 months	11 years, 3 months	3 years, 5 months				

development, for three times. Each session lasted approximately 30 min. Mental age (Raven and PPVT-R) was assessed during the first session, whereas number and arithmetic knowledge (BIN) was assessed during the second session. The number-to-position task was administered during the third session.

3. Results

3.1. Numerical intelligence and arithmetic knowledge

Scores only for DS and TD-MA children in numerical intelligence and arithmetic knowledge tests are shown in Table 2. As previously reported in Sella, Lanfranchi, et al. (2013), the total score for numerical intelligence did not significantly differ in the two groups, although individuals with DS showed a significantly higher score in lexical tasks. Likewise, arithmetic knowledge did not differ in the two groups, although individuals with DS showed significantly lower performance in the non-verbal calculation task (see *t*-tests in Table 2).

Because the number of subjects per group was below 30, Spearman rank correlations were calculated (see Siegel & Castellan, 1988, for details) between numerical abilities (numerical intelligence and arithmetic knowledge scores), cognitive abilities (Raven score) and experience (age). Results showed, in individuals with DS, significant correlations between the Raven and both numerical intelligence ($r = .49$, $p < .05$), and arithmetic knowledge ($r = .70$, $p < .01$). In the TD-MA group, a significant correlation was found between numerical intelligence and chronological age ($r = .53$, $p < .05$).

3.2. Number line task

Children's estimation accuracy was computed as the percentage of absolute error (PE). This was calculated with the following equation (Siegler & Booth, 2004):

$$\mathrm{PE} = \frac{\text{Estimate} - \text{target number}}{\text{Scale of estimates}} \times 100$$

For example, if the estimated position of 45 on the 0–100 interval corresponds to 60, the PE corresponds to 15% (i.e., $((60 - 45)/100) \times 100$).

A one-way ANOVA on mean PE was computed for each interval with group (DS, TD-MA, TD-CA) as between subjects factor. For the 1–10 interval, results indicated that the three groups were significantly different, $F_{(2,60)} = 11.21$, $p < .001$, $\eta^2 = .27$. Subsequent post hoc comparisons showed that the DS group performed as well as the TD-MA group and both groups performed worse than the TD-CA group (both $p < .001$). PEs for DS, TD-MA and TD-CA were 12.8%, 10% and 4.6%, respectively. Results for the 0–100 interval also indicated that the three groups were significantly different $F_{(2,60)} = 70.66$, $p < .001$, $\eta^2 = .70$. However, in this case, subsequent post hoc comparisons showed that the DS group performed better than the TD-MA group ($p < .001$), and worse than the TD-CA group ($p < .001$). PEs for DS, TD-MA and TD-CA were 15.8%, 24.9% and 4%, respectively.

Fits for linear and logarithmic functions (r^2) were computed to analyze the pattern of estimates. Following Siegler and Opfer (2003), these fits were first computed on group medians and then for each individual child.

3.2.1. Group analysis

For the 1–10 interval, the fit of the linear model was significantly better than the fit of the logarithmic model in all groups (DS: R^2 lin = 99% vs R^2 log = 95%; $t_{(6)} = 4.81$, $p < .01$; TD-MA: R^2 lin = 99% vs R^2 log = 95%; $t_{(6)} = 4.72$, $p < .01$; TD-CA: R^2 lin = 99% vs R^2 log = 97%; $t_{(6)} = 4.67$, $p < .01$). For the 0–100 interval, the best fitting model for both DS and TD-MA groups was logarithmic (DS: R^2 lin = 87% vs R^2 log = 97%; $t_{(9)} = 6.32$, $p < .01$; TD-MA: R^2 lin = 62% vs R^2 log = 90%, $t_{(9)} = 5.69$, $p < .001$). For the TD-CA group, the best fitting model was linear (R^2 lin = 99% vs R^2 log = 87%, $t_{(9)} = 7.90$, $p < .001$). Median estimates and best fitting function for each group and interval are shown in Fig. 1.

Table 2
Means (and standard deviations) of DS and TD-MA groups in the numerical intelligence and the arithmetic knowledge tests.

	DS	TD-MA	$t_{(40)}$
Numerical intelligence	85.1 (18.5)	79.0 (27.6)	1.1
Lexical process	21.5 (3.5)	16.4 (5.9)	3.4**
Semantic processes	16.7 (3.5)	18.2 (2.6)	−1.6
Counting	31.6 (9.6)	30.5 (7.6)	.4
Pre-syntactic proc.	14.4 (4.4)	15.1 (4.7)	−.5
Arithmetic knowledge	7.4 (4.6)	7.6 (2.2)	−.2
Non-verbal calc.	2.9 (1.8)	4.1 (1.5)	−2.2*
Story problems	1.9 (1.3)	1.7 (1.4)	.5
Number facts	2.6 (1.8)	1.9 (1.1)	1.7

* $p < 0.05$.
** $p < 0.01$.

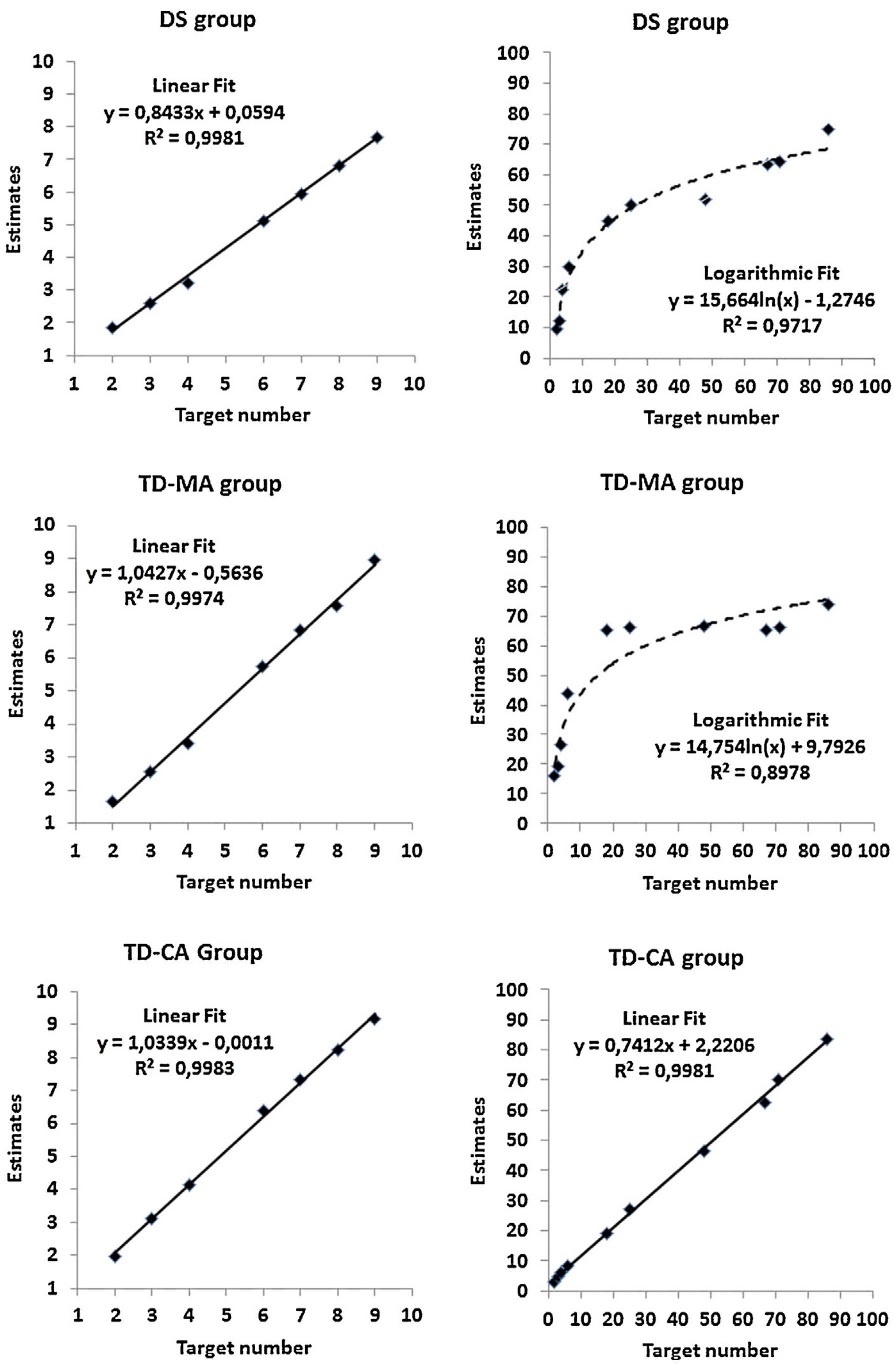

Fig. 1. Median estimates and best fitting function as a function of group. Left: 1–10 number line; right: 0–100 number line.

3.2.2. Individual analysis

Regression analyses were performed on the data of individual children. The best fitting model between linear and logarithmic was attributed to each child, whenever significant (e.g., the child was attributed a logarithmic mapping for a given interval if the highest r^2 was logarithmic). If both failed to reach significance, the child was considered as not having a reliable mapping for that specific interval. For each interval, children were therefore classified as having a linear, logarithmic, or no mapping (Table 3).

In the 1–10 interval, the majority of children in all groups showed a linear mapping ($p < .01$). However, in the 0–100 interval the majority of children in the DS and in the TD-MA groups showed a logarithmic mapping ($p < .01$), while the majority of children in the TD-CA group showed a linear mapping ($p < .01$). Thus, children in both the TD-MA and DS groups

Table 3
Distribution of children (%) as a function of group and task.

Task	Type of mapping		
	None	Logarithmic	Linear
1–10 Interval			
DS	0	14.3	85.7
TD-MA	4.8	9.5	85.7
TD-CA	0	19	81.0
0–100 Interval			
DS	0	76.2	23.8
TD-MA	0	90.5	9.5
TD-CA	0	4.8	95.2

rely on an intuitive, logarithmic mapping when the numerical context is difficult or unfamiliar, whereas when the numerical context is familiar, they use a linear mapping.

A one way ANOVA on linear r^2 was run in order to explore differences in linearity between the three groups. In the 1–10 interval a significant effect of group was found, $F_{(2,62)} = 3.15$, $p = .05$, $\eta^2 = .10$. Subsequent post hoc comparisons showed higher values in TD-CA group than in DS group. Also in the 0–100 interval a significant effect of group was found, $F_{(2,62)} = 38.06$, $p < .001$, $\eta^2 = .57$. Subsequent post hoc comparisons showed that TD-CA had higher values with respect to both TD-MA and DS groups (in both cases $p < .001$), and that DS group had higher values than TD-MA ($p < .001$).

Spearman rank correlations between linearity of estimation and Raven, PPVT-R, age and years of schooling were also separately calculated for the DS and TD-MA group, in order to investigate the relationship between linearity, cognitive (verbal and visuo-spatial) level and experience. For the 1–10 line, linearity for the DS group was significantly related to the Raven score ($r_s = .44$, $p < .05$), while for the TD-MA group it was significantly related to age ($r_s = .43$, $p = .05$). Linearity on the 0–100 line showed no significant correlations for both groups.

4. Discussion

In the present work we investigated numerical estimation in individuals with DS. As noted in the Introduction, there are two competing explanations for the mathematical difficulties of individuals with DS. One hypothesis is that the difficulties stem from low general cognitive level, which implies that individuals with DS should perform in line to their mental age (i.e. *developmental hypothesis*; Zigler, 1969), whereas the other hypothesis is that the difficulties reflect a specific impairment in DS cognitive profile (i.e. *difference hypothesis*; Gelman & Cohen, 1988; Nye et al., 2001).

Our results show that the performance of individuals with DS is well aligned with that of TD children matched for MA. Indeed, DS and TD-MA did not differ on most subtests of a numerical intelligence battery as well as on arithmetical knowledge tasks. Individuals with DS performed worse than TD-MA children only in a non-verbal calculation task, whereas they outperformed controls in tasks that tap the lexical knowledge of numbers (reading, writing, and transcoding of Arabic numbers). The latter result can be attributed to the longer exposure to numbers for the individuals with DS due to their much higher chronological age and number of years at school. Numerical intelligence and arithmetical knowledge scores were correlated to intelligence (Raven) in the DS group, while in the TD-MA group they were mainly correlated with experience (age). These results suggest that basic numerical abilities tend to be in line with mental age in individuals with DS although they might show some specific difficulty in non-verbal calculation. Given that the latter task (in our study) involved addition or subtraction for small sets of dots, it is conceivable that the difficulty is linked to the Object Tracking System that supports the enumeration of small sets of objects (Feigenson et al., 2004; Trick & Pylyshyn, 1994) and has been found to be impaired in DS (Sella, Lanfranchi, et al., 2013).

With regard to number estimation, the performance of individuals with DS paralleled that of TD-MA children and both groups performed worse than TD-CA children in the 1–10 number line, even though the mapping was linear for all groups in terms of median estimates. Moreover, individuals with DS performed better than TD-MA children and worse than TD-CA children in the 0–100 number line. In this case both DS and TD-MA children showed mainly a logarithmic mapping, while TD-CA children showed a linear mapping. Finally the linearity correlated with mental age in individuals with DS while it correlated with age in TD children. Note that the coexistence of different spatial patterns for smaller and larger intervals has been repeatedly found in typical development (Berteletti et al., 2010; Siegler & Booth, 2004; Siegler & Opfer, 2003). In this regard, our data are fully in line with the previous studies.

Logarithmic coding of numbers is a hallmark of the Approximate Number System subserving the non-symbolic representation of numerosities (Feigenson et al., 2004). Studies on typical development showed a developmental pattern with increasing precision of mapping, consistent with increasing ability to discriminate the numerosity of two sets (i.e., number acuity; Halberda & Feigenson, 2008; Piazza et al., 2010). Notably, numerosity discrimination in individuals with DS appears to be in line with mental age (Camos, 2009; Paterson et al., 2006; Sella, Lanfranchi, et al., 2013). The present finding that numerical estimation in DS is well aligned to mental age is therefore consistent with the hypothesis that the representation of quantity is relatively preserved (see Sella, Lanfranchi, et al., 2013, for further discussion).

Taken together our results suggest that number estimation and the transition between logarithmic and linear mapping in DS are tied to cognitive level (mental age). Indeed, performance in the number line task was linked to the non-verbal intelligence score. Nevertheless, in the 0–100 interval individuals with DS performed better than TD-MA children, although both groups deployed the logarithmic mapping that is typical of younger children (e.g., Berteletti et al., 2010). This difference suggests that length of experience with numbers can play a role in shaping the pattern of estimates. Indeed, age and experience with a given numerical range is the major determinant of the transition between logarithmic and linear mapping in TD children (e.g., Berteletti et al., 2010; Berteletti et al., 2012; Siegler & Opfer, 2003), although it is worth noting that perfect knowledge of the number sequence in a given range is not a sufficient condition for linearity in the estimation of the same items (Berteletti et al., 2012).

5. Conclusions

In summary our results suggest that in children with DS numerical abilities and in particular numerical estimation tend to be in line with mental age, supporting the developmental hypothesis.

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