Research in Developmental Disabilities 41–42 (2015) 58–65

Contents lists available at ScienceDirect

Research in Developmental Disabilities

Numerical and area comparison abilities in Down syndrome

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form 2 May 2015
Accepted 25 May 2015
Available online

Keywords:
Down syndrome
Eye-tracking task
Numerical cognition
Number comparison abilities
Area comparison abilities

ABSTRACT

Individuals with Down syndrome (DS) have great difficulty in learning mathematics. In recent years, research has focused on investigating whether precursors of later mathematical competence, such as estimating and comparing numerosities, are preserved in DS. Although studies have suggested a strong relationship between the ability to compare continuous quantities (e.g., area of an object) and that of comparing numerosities, it is still unknown whether this ability is preserved in DS. This study investigated the abilities of individuals with DS to compare area and number and contrasted them with those of two control groups of typically developing individuals. Participants were 16 individuals with DS, 16 typically developing individuals matched by mental age (MA group), and 16 typically developing individuals matched by chronological age (CA group). All participants performed two eye-tracking tasks: an Area Comparison Task (ACT) and a Number Comparison Task (NCT). Stimuli in the two tasks differed in the same ratio to enable comparison of individual performance across both tasks. The results showed that in general, the performance of the three groups was better in the ACT than in the NCT. Critically, performance of individuals with DS in both tasks was consistent with that of individuals with the same MA. The study shows that the abilities to compare area and numerosity are both preserved in DS, and that individuals with this syndrome, like typically developing individuals, show better performance in comparing area than number.

1. Introduction

Down syndrome is a genetic disorder caused by an extra copy of the chromosome 21, and it is the leading cause of intellectual disability (Lubec & Engidawork, 2002). Individuals with Down syndrome (DS) have difficulty with several mathematical abilities (for a review see Brigstocke, Hulme, & Nye, 2008), including greater difficulty in solving simple arithmetic problems (Paterson, Girelli, Butterworth, & Karmiloff-Smith, 2006) and in understanding the principles of counting (Gelman & Cohen, 1988) than typically developing children with the same mental age.

Recent studies have searched for the causes of these difficulties by investigating whether the two core systems of number, the Approximate Number System (ANS) and the Object Tracking System (OTS), are preserved in individuals with DS (Camos, 2009; Sella, Lanfranchi, & Zorzi, 2013). These two systems are thought to be the origin of our

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http://dx.doi.org/10.1016/j.ridd.2015.05.008
0891-4222/

understanding of number and later mathematical abilities (Carey, 2009; Feigenson, Libertus, & Halberda, 2013). The ANS allows for the rough estimation and comparison of the number of objects in collections, and its precision is determined by the ratio between two quantities to be compared (Halberda, Mazzocco, & Feigenson, 2008). The OTS allows for exact judgments of small numerosities of up to four objects (Feigenson, Carey, & Hauser, 2002). Research has shown that individuals with DS have a preserved ANS but an impaired OTS. Sella et al. (2013), using a task in which children had to indicate whether a numerosity matched one previously shown, found that children with DS with a mean mental age of 4.92 years performed as well at matching numerosities larger than four as their typically developing peers of the same mental age. These results are consistent with a previous report showing that children with DS performed as well as children of the same mental or chronological age at comparing larger numerosities (8 vs. 16 and 8 vs. 12) (Camos, 2009). Infants with DS, however, have difficulty with comparing small numerosities (2 vs. 3) (Paterson et al., 2006). Finally, two other numerical abilities supported by the ANS are relatively preserved in individuals with DS: numerical estimation and approximate addition. Lanfranchi, Berteletti, Torrisi, Vianello, and Zorzi (2015) reported that numerical estimation of children with DS is comparable to that of typically developing children with similar mental age. Belacchi et al. (2014) found that individuals with DS performed as well in an approximate addition task as a group matched by fluid intelligence.

A strong relationship has been suggested between the abilities to discriminate number and quantities like area (Brannon, Lutz, & Cordes, 2006). In fact, current theories of magnitude processing have proposed that all kinds of magnitudes (e.g., number, time, and space) are computed by one general system (Lourenco & Longo, 2011; Walsh, 2003). Evidence to support this proposal comes from studies with typically developing infants, which have reported that six-month-olds have the same ability to discriminate numerosity and area up to a ratio of 1:2 (Brannon et al., 2006; Xu & Spelke, 2000). In Xu and Spelke (2000), infants were habituated to a numerosity (8 or 16 dots); however, stimuli varied in continuous features (e.g., total area, dot size). In Brannon et al. (2006), infants were habituated to one size of an Elmo face. Critically, although the complexity of the stimuli were different (e.g., in Xu and Spelke, stimuli changed not only in numerosity, but also in other continuous features), infants dishabituated to two-fold changes, that is, to a new numerosity that was either double or half, or to an Elmo face that was twice the size of the original. In childhood as well as in adulthood, better performance has been reported for area comparison than for number comparison tasks (Odic, Libertus, Feigenson, & Halberda, 2012). To the best of our knowledge, there has been no investigation of the ability of individuals with DS to compare quantities other than number. It thus remains unknown whether individuals with DS show a typical development of quantity discrimination.

Atypical development can provide crucial insights into the ability to discriminate different kinds of magnitudes (Allman, Pelphrey, & Meck, 2012). Various studies have shown how genetic disorders and their particular cognitive profiles lead to greater deficits for some magnitudes than for others. Rousselle, Dembour, and Noël (2013) reported that the ability of individuals with William syndrome (WS), a genetic disorder caused by a deletion on chromosome 7q11.23, to compare number, length, and duration was aligned with that of children of the same non-verbal mental age; their performance in comparing numerosity and length, but not duration, was significantly less than that of children of similar verbal ability. This pattern of performance was predicted based on the cognitive profile of WS, where language skills are relatively preserved but visuospatial abilities are impaired. The study (Rousselle et al., 2013) found that individuals matched by verbal mental age were older (7.5 years) than those matched by non-verbal age (6.08 years); that is, verbal abilities were more preserved than visuospatial ones.

Previous research has demonstrated that DS is characterized by relatively preserved visuospatial abilities but impaired language skills (Moldabsky, Lev, & Lerman-Sagie, 2001; but see Yang, Conners, & Merrill, 2014). One would expect that this relative visuospatial ability would predict relative ability in comparing both area and numerosity. As a consequence, if the ability of individuals with DS to compare both area and large numerosities are preserved, we should find a pattern similar to that reported in typically developing children, that is, better performance at comparing area than number (Odic et al., 2012). Current theories of number development have stressed the importance of continuous quantity discrimination in early number processing (Cantrell & Smith, 2013; Leibovich & Henik, 2013), and testing this prediction could provide important information about the ability of individuals with DS to improve their numerical processing.

The present study investigated whether the ability to compare area is preserved in DS, and contrasted it with the ability to compare numerosity. The comparison of area was chosen because of its close relationship to number discrimination (Cordes & Brannon, 2008). Two eye-tracking tasks were performed: an Area Comparison Task (ACT) and a Number Comparison Task (NCT). An eye-tracking paradigm was used that kept the tasks as simple as possible for individuals with DS.

Recent studies have shown the benefits of using eye-tracking measures to evaluate cognitive processes in individuals with developmental disabilities (Brady, Arderson, Hahn, Obermeier, & Kapa, 2014), and such fine-grained measures as the duration of visual attention might be a more sensitive measure of differences in performance than correct/incorrect responses. This study used two eye-tracking tasks, in which participants saw images displaying two objects differing in size (ACT) or two collections differing in numerosity (NCT). Participants were asked to look at the image with the larger object or the larger numerosity. The abilities of individuals with DS were compared with two different typically developing control groups: one of similar mental age and another of similar chronological age.

2. Materials and methods

2.1. Participants

Participants in this study were 16 individuals with DS (7 female) with a mean chronological age (CA) of 12.29 years (range 3.83–22.42 years) and with a mean mental age (MA) of 4.27 years (range 2.3–7.4 years). Their performance was compared with that of two control groups of 16 typically developing individuals: one matched for sex and CA, and another matched for sex and MA. The mental age of individuals with DS and members of the MA group was determined using either an abbreviated version of the Wechsler Preschool and Primary Scale of Intelligence-III (WPPSI-III, Wechsler, 2002) or the Wechsler Intelligence Scale for Children-IV (Wechsler, 2007), according to their chronological age. The former included the subtests Receptive Vocabulary, Object Assembly, and Block Design, and the latter Block Design, Matrix Reasoning, and Picture Completion. These versions are among the ten most recommended abbreviated versions, and both have high reliability (both .93) and validity scores (.74 and .83, respectively), as reported by Sattler (2010). There were no significant differences between the MA of the DS and MA group, or between the CA of the DS and CA group (all p values $> .05$). See Table 1 for detailed statistics.

Twelve additional individuals with DS participated in the study; however, they were excluded because of experimental error ($n = 1$) or because they did not complete the minimum number of trials required ($n = 11$; see Section 3).

2.2. Experimental tasks

2.2.1. Visual stimuli

For the Area Comparison Task (ACT), visual stimuli were six color cartoon images of food: a candy, a cookie, an ice cream cone, a cupcake, a slice of pizza, and a strawberry. There was a standard size for all images (39,600 pixels) and two other sizes that could be either larger or smaller than the standard one. The larger and smaller images differed from the standard by the same ratio: for example, the smaller cookie was 26,444 pixels, while the larger was 59,499 pixels; both images differed from the standard by a ratio of 2:3. Each image was centered in a gray frame of 800×600 pixels (see Fig. 1a).

For the Number Comparison Task (NCT), visual stimuli were six color cartoon images of animals: bears, cats, dogs, horses, monkeys, and rabbits. The NCT was analogous to the ACT, featuring a standard numerosity (12 animals of the same kind), and two images that depicted either a greater or lesser numerosity. There were, for example, three images depicting collections of monkeys: a standard image with 12 monkeys, and two others with 18 and 8 monkeys each. The latter two numerosities both differed from the standard by the same ratio: 2:3 in this example. In order to prevent children from using continuous variables as a cue to solve the task, the total surface area of all the images, regardless of numerosity, was the same. Five different sizes of animals were used within each image to prevent children from using the size of an individual animal as a cue. The animal images were pseudorandomly distributed in a gray frame of 800×600 pixels; care was taken to avoid presenting visual stimuli close to the corners (see Fig. 1b). See Table 2 for a detailed description of the numerosities and the sizes employed in each task.

2.2.2. Audio stimuli

Two questions were employed: *¿Dónde hay más?* (Where are there more?), and *¿Cuál es más grande?* (Which one is larger?). These sentences were digitally recorded by a female native Spanish speaker; they were edited to remove background noise and match peak-to-peak amplitude.

2.2.3. Design

Each of the two tasks consisted of 20 trials that presented four different ratio comparisons. There were four trials of the 1:3 ratio, four of the 1:2 ratio, six of the 2:3 ratio, and six of the 3:4 ratio. The imbalance in the number of trials was intended to provide participants with a larger number of trials of the more difficult ratios. Similar designs have been used in previous studies (Halberda & Feigenson, 2008). The trials were divided into four blocks of five trials each. Before the beginning of each block, an animation was displayed in the center of the screen in order to capture participants' attention. Four versions of each task were used to balance the order of trial presentation, target side, and type of ratio.

All trials lasted 3800 ms, beginning with the appearance of two gray frames embedded in a 1920×1080 pixel blue background, while participants heard one of the two questions: *¿Dónde hay más?* (Where are there more?) for the NCT, and

Table 1
Group characteristics.

	DS group M (SD)	MA group M (SD)	CA group M (SD)	t (16)
Chronological age	12.48 (5.52)	4.34 (1.48)	12.32 (5.38)	1.45[a]
Mental age	4.31 (1.47)	4.36 (1.50)	*n.a.*	0.57

[a] The t value is for the comparison between the DS group and the CA group.

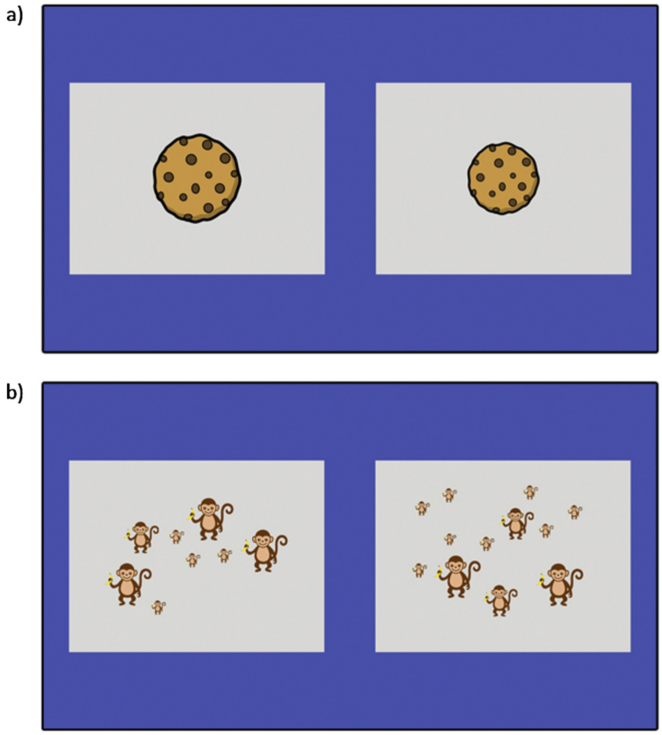

Fig. 1. Stimuli used for the 2:3 ratio comparison for (a) the Area Comparison Task (59,499 pixels vs. 39,666 pixels) and (b) the Number Comparison Task (8 vs. 12).

Table 2
Object areas (pixels) and numerosities used in the Area Comparison Task and Number Comparison Task for each ratio employed.

	Ratio			
	1:3	1:2	2:3	3:4
Area Comparison Task	39,666 vs. 13,222	39,666 vs. 19,833	39,666 vs. 26,444	39,666 vs. 29,749.5
	118,998 vs. 39666	79,332 vs. 39666	59,499 vs. 39,666	52,888 vs. 39,666
Number Comparison Task	12 vs. 4	12 vs. 6	12 vs. 8	12 vs. 9
	36 vs. 12	24 vs. 12	18 vs. 12	16 vs. 12

¿Cuál es más grande? (Which one is larger?) for the ACT. At the offset of the question, at 1300 ms, the images appeared inside the gray frames and remained static for 2500 ms. This period of 2500 ms was considered for the statistical analyses.

2.3. Procedure

Stimuli were presented on a 23-inch LED monitor (screen resolution 1920 × 1080 pixels). A portable eye-tracker (Tobii X2-30) was placed in the lower area of the monitor frame. The Tobii X2-30 captured the binocular gaze position (*X* and *Y* coordinates) every 30 ms. Stimulus presentation and data storage were carried out using Tobii Studio software. Presentation of the experimental tasks started with a five-point infant calibration. Participants were seated 65 cm from the screen.

Participants were evaluated in a quiet room in the laboratory or at their school. For the DS and MA groups, the session started with assessment of mental age, followed by a 10-min break, and then the presentation of the two experimental tasks; the CA group began with the two tasks. Task order was balanced in all three groups: half the participants saw the ACT first, while the other half saw the NCT first. Before the presentation of the experimental tasks, participants performed four practice trials in which two paper cards were placed in front of the participants and they were asked to point to the card depicting either the larger numerosity or the larger object. The numerosity or sizes of the images in the practice trials were in a 1:5 ratio, a ratio not employed in the experimental tasks. Incorrect answers in the practice trials were corrected by the experimenter; however, errors were highly infrequent. In the experimental trials, unlike the practice trials, participants were merely told that they were going to look at some images; pointing by participants was infrequent. The entire session, including assessment of mental age and presentation of the experimental tasks, lasted approximately 50 min.

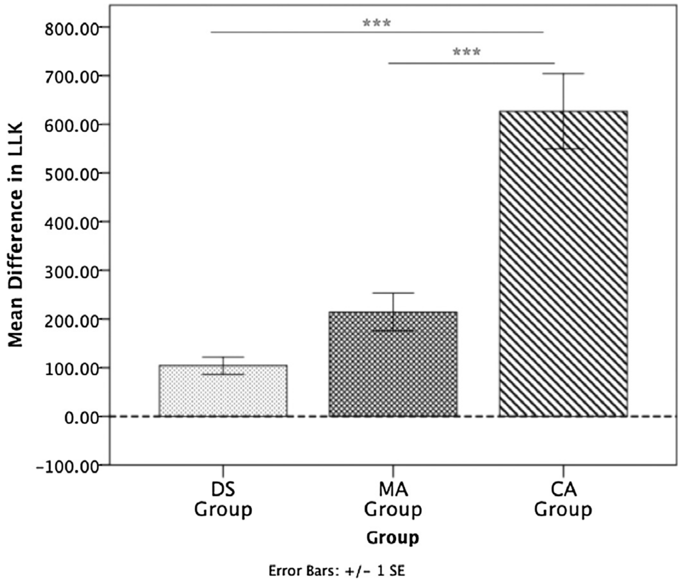

Fig. 2. Mean (±1 SE) Difference in LLK by group. Dotted line represents chance level. ***$p < .001$.

3. Results

For each experimental trial, two areas of interest (AOI) were created: one for the target (T) and one for the distractor (D). The target was defined as the image with the larger area or the larger numerosity. AOIs coincided with the gray frames in which the stimuli were embedded. Trials were excluded in which participants did not look at least 10% (250 ms) of the time at each image, or where they did not look at least 40% (1000 ms) of the duration of the trial. Participants were also excluded ($n = 11$) who did not present at least seven of the eight types of trials (4 ratios × 2 tasks). Of the 960 NCT trials originally presented, 669 trials (69%) were analyzed: 159 from the DS group, 277 from the CA group, and 233 from the MA group. Of the 960 ACT trials presented, 655 (68%) were analyzed: 227 from the DS group, 197 from the CA group, and 231 from the MA group.

We first calculated the Difference in Longest Look (LLK) (Schafer & Plunkett, 1998), which is the difference between the single longest look at the target and the single longest look at the distractor. A positive LLK indicates preference for the target

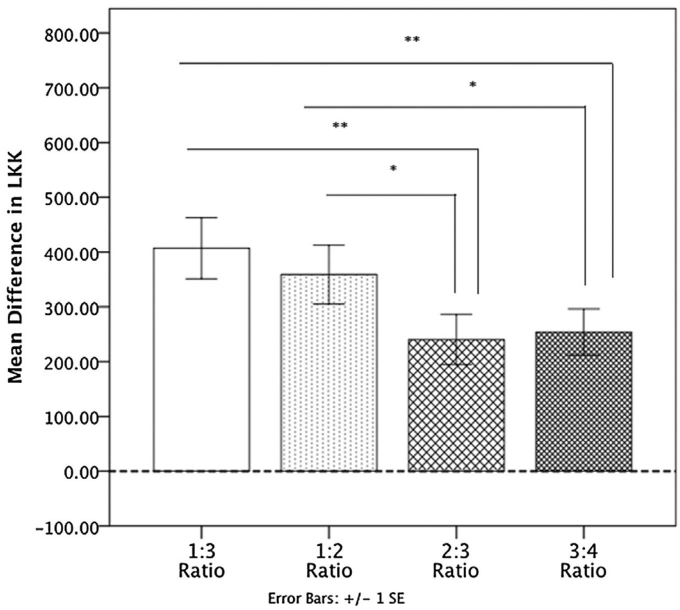

Fig. 3. Mean (±1 SE) Difference in LLK by ratio with the data of the three groups collapsed. Dotted line represents chance level. *$p < .05$, **$p < .01$.

over the distractor, while negative LLK indicates the opposite; a value of zero corresponds to chance. For each participant, this Difference in LLK was averaged across trials for the four ratios (1:3, 1:2, 2:3, and 3:4) and the two tasks (ACT and NCT), producing eight data points per participant.[1]

A $3 \times 2 \times 4$ mixed-design repeated measures ANOVA with Group (DS, MA, and CA groups) as between-subjects factor, and Task (ACT and NCT) and Ratio (1:3, 1:2, 2:3, and 3:4) as within-subjects factors, with Difference in LLK as the dependent measure, revealed a significant effect of Group ($F(2,45) = 29.19$, $p < .001$, partial $\eta^2 = .56$), Task ($F(1,45) = 27.41$, $p < .001$, partial $\eta^2 = .37$), and Ratio ($F(3,43) = 6.08$, $p < .01$, partial $\eta^2 = .29$). None of the interactions were statistically significant.

To further explore the effect of Group, we used Bonferroni corrected post hoc comparisons ($\alpha = .05$), which revealed significant differences between the DS and CA groups ($p < .001$), and between the MA and CA groups ($p < .001$). There were no significant differences between the DS and MA groups ($p > .05$) (see Fig. 2). The effect of Task was driven by participants' performance in the ACT ($M = 414.62$ ms; SD = 333.97) in comparison to the NCT ($M = 215.56$ ms; SD = 323.84). Finally, the Ratio effect showed that participants' performance decreased as the difference decreased between the two stimuli under comparison. Bonferroni corrected post hoc comparisons for exploring the Ratio effect revealed significant differences between the 1:3 (407.11 ms) and the 2:3 (240.28 ms; $p < .01$), as well as the 3:4 (254.09; $p < .01$). There were also significant differences between the 1:2 (358.88 ms) and the 2:3 (240.28 ms; $p < .05$), as well as between the 1:2 and the 3:4 (254.09 ms; $p < .05$) (see Fig. 3). Importantly, although participants performed differently across ratios, performance was better than chance level in all of them (all p values were $< .001$).

4. Discussion and general conclusions

This study investigated whether the ability of individuals with DS to compare area was preserved, and to contrast that ability with their ability to compare numerosity. Individuals with DS performed two eye-tracking tasks in which they had to compare either the areas of two objects or the numerosities of two collections. Their performance was compared with that of two control groups: individuals matched by MA and individuals matched by CA. Individuals with DS performed in both tasks as expected for their MA. In addition, they exhibited the same pattern found in typically developing individuals: their performance showed a ratio effect (i.e., performance decreased as the ratio between the stimuli to be compared decreased), and they were better at comparing area than numerosity (Odic et al., 2012).

Theories of number development have proposed the ANS (the system thought to support our "numerical intuition") as one of the main building blocks for later mathematical abilities (Dehaene, 1997; Feigenson et al., 2013). For this reason, various studies have looked at comparison and estimation abilities—those supported by the ANS—of individuals with DS to explain the origin of their mathematical difficulties (Camos, 2009; Lanfranchi et al., 2015; Sella et al., 2013). However, these studies have reported that individuals with DS have a relatively preserved ANS. The results of the present study confirmed these observations and shed light on inconsistent results. Camos (2009), for example, found no differences in performance in comparing numerosities between individuals with DS and others with the same CA. In our study, however, there are two possible explanations for the better performance of the CA group in comparison with the DS group: (1) the presentation of a more difficult ratio (3:4), and (2) the sensitivity of an eye-tracking measurement. In contrast to Camos (2009), we employed a 3:4 ratio, the smallest difference that children can detect at age four, the mean mental age of the DS and MA group (Halberda & Feigenson, 2008; Odic et al., 2012). Moreover, the variable we measured, Difference in LLK, might be more sensitive to differences in performance than binary correct/incorrect responses. Difference in LLK not only tells us whether participants chose the larger numerosity or area, but also the duration of the comparison processing—the longest look at the target or the distractor.

The cognitive profile in DS has been characterized by a general advantage in visuospatial abilities, which leads us to predict that individuals with DS may, consistent with their MA, have a relatively preserved ability to compare the areas of objects. Previous research has shown that individuals with this syndrome have also preserved the ability to compare large numerosities (Sella et al., 2013). The performance of individuals with DS in this study did not differ from the performance of their MA peers, suggesting that both abilities were indeed preserved.

Studies of typically developing individuals have reported better performance at comparing the areas of objects than comparing numerosities (Odic et al., 2012). We would expect to find such a pattern in DS if these abilities were aligned with MA, and indeed it was found in the performance of all groups, including the DS group.

Various authors have stressed the importance of developing continuous quantity discrimination to improve numerical abilities (Leibovich & Henik, 2013). A recent study, in fact, showed that typically developing individuals with difficulties in learning mathematics have impaired ability not only in comparing numerosities, but also in comparing continuous quantities like time (Skagerlund & Träff, 2014). Such deficits have not been reported in the case of individuals with DS. Our study showed that the abilities to discriminate numerosity and continuous quantities like area are preserved in DS according to MA. Further research is needed to understand the origin of the difficulties that individuals with DS experience in mathematical learning. The current state of the research suggests a possible origin in OTS impairment (Paterson et al., 2006; Sella et al., 2013).

[1] For cases in which participants completed seven out of the eight trials, missing values were replaced by the mean group for the missing task and ratio. Of the 384 data points (48 participants $\times$ 8 types of trials), only nine were replaced (2%).

The findings presented here could have implications in clinical practice with individuals with DS. As previously mentioned, individuals with DS have difficulty in comparing small numerosities, and previous research has suggested that the OTS is highly sensitive in infancy to continuous information such as area and length (Clearfield & Mix, 1999; Feigenson, Carey, & Spelke, 2002). Therefore, individuals with DS might be using area information to compensate for their impaired OTS. If that is the case, clinicians might improve children's number comparison abilities by teaching them to disregard irrelevant information when comparing numerosities in the range of the OTS.

A limitation of the current study is that the tasks presented here not only differed in the magnitudes to be compared, but also in the complexity of the stimuli. In the NCT, participants not only had to compare different numerosities, but also had to ignore irrelevant features of the stimuli (e.g., object size). The ACT was more straightforward: the stimuli differed only in size. An alternative interpretation of the better performance of the three groups in the ACT than in the NCT could be related to their ability to overcome the complexity of the stimuli. Nonetheless, the Ratio effect found (that performance decreased as the difference decreased between the stimuli under comparison, regardless of the task), suggests that participants were relying on magnitude information, that is, number and area, to make their judgments. One of the features shared by magnitudes is that their discriminability varies as a function of the ratio difference of the stimuli (Lourenco & Longo, 2011). More importantly, although in some trials the different sizes of the objects may have helped to find the image with the larger numerosity, this information was not consistent across the task; the numerosity of the set was the only information that varied consistently with the tested ratio. Future work should look at the influence of stimulus complexity on the relationship between the ability to compare area and number.

Another possible limitation is that we did not calculate individuals' acuity of ANS (i.e., the value of w). Although there is a high correlation ($r = -.94$)[2] between individuals' accuracy in a comparison task and the value of w (Gilmore et al., 2013), experimental designs that allow the calculation of this measure have the benefit of showing the smallest ratio that an individual or group can discriminate.

Overall, this study suggests that, although the abilities of individuals with DS to compare area and number are severely behind those of individuals of the same CA, these abilities are consistent with their mental age, and they show the pattern previously reported for typically developing individuals.

Acknowledgements

This research was supported by funds awarded to the second author: Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT RN309214), and the Foundation Jérôme Lejeune (Project: Language Comprehension in Down Syndrome). We would like to thank all the institutions, children, adolescents, and families who participated in this study. We also thank Ethelmar Vázquez Pérez for her assistance with data collection.

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[2] The correlation between these two measures is negative because the smaller the value of w, the smaller is the ratio comparison that can be made.

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