Evidence of the impact of visuo-spatial processing on magnitude representation in 22q11.2 microdeletion syndrome

Short title: The impact of visuo-spatial processing on magnitude representation

Lucie Attout[1,2], Marie-Pascale Noël[2] , Line Vossius[1] & Laurence Rousselle[1]

[1] Research Unit "Enfances", University of Liège, Belgium

[2] Psychological Sciences Research Institute, Catholic University of Louvain, Louvain-la-Neuve, Belgium

Address for correspondence:

Dr. Lucie Attout

Research Unit "Enfances"

Université de Liège

Boulevard du Rectorat, B33, 4000 Liège – Belgium

Tel: 0032 4 36626

Email: lucie.attout@ulg.ac.be

ABSTRACT

The influence of visuo-spatial skills on numerical magnitude processing is the subject of a long-standing debate. As most of the numerical and non-numerical magnitude abilities underpinning mathematical development are visual by nature, they are often assessed in the visual modality, thereby confusing visuo-spatial and numerical processing. In order to assess the influence of visuo-spatial processing on numerical magnitude representation, we examined magnitude processing in patients with 22q11.2 deletion syndrome (22q11DS), a genetic condition characterized by a cognitive profile with a relative weakness in visuo-spatial abilities but with preserved verbal abilities. Twenty-seven participants with 22q11DS were compared to two control groups (one matched on verbal intelligence and the other on visuo-spatial abilities) on several magnitude comparison tasks each with different visuo-spatial processing requirements. Our results showed that participants with 22q11DS present a consistent pattern of impairment in magnitude comparison tasks requiring the processing of visuo-spatial dimensions: comparison of lengths and collections. In contrast, their performance did not differ from the control groups in a visual task with no spatial processing requirement (i.e. numerical comparison of flashed dot sequences) or in auditory tasks (i.e., duration comparison and numerical comparison of sound sequences). Finally, a specific deficit of enumeration processes was observed in the subitizing range. Taken together, these results show that deficits in magnitude can occur as a consequence of a visuo-spatial deficit. This highlights the influence of the nature of the tasks selected to assess magnitude representation.

236 words

INTRODUCTION

One of the most influential models in the field of numerical cognition assumes that there is a specific system for the representation of number magnitude. As the resulting representation is thought to be approximate, this system has been called the approximate number system (ANS). The ANS is believed to be shared by many species and would allow the discrimination, the comparison, the addition, and the subtraction of numerosities presented in and across different formats and modalities (i.e. comparing the number of objects seen or touched, the number of tones or voices, the number of perceived events; Féron, Gentaz, & Streri, 2006; Izard, Sann, Spelke, & Streri, 2009; Kobayashi, Hiraki, & Hasegawa, 2005). The resulting approximate number representation is therefore considered to be independent of the modality (Barth, Kanwisher, & Spelke, 2003; Barth et al., 2006; Meck & Church, 1983). One seminal model has been proposed by Dehaene and Changeux (1993) to explain how this amodal number magnitude representation is extracted from visual arrays. Detailing this model is beyond the scope of this paper but the crucial assumption for the issue considered here is that each element in the visual display would be represented with a constant amount of activation in the process, regardless of its size or its other perceptual properties, resulting in a cumulated activity which is highly correlated with the numerosity of the set. Thus, the numerosity representation would not be derived from perceptual cues such as area, density, etc., but extracted from specific mechanisms of perceptual normalization that eliminate the perceptual cues confounded with numerosity.

However, an increasing amount of empirical evidence argues against the amodality of the number magnitude representation and indicates that numerical processing is dependent on perceptual and visuo-spatial processing at different levels. Indeed, a large number of studies have shown that numerical judgments are highly influenced by the visual perceptual

properties of the stimulus (e.g. density, sum of perimeter, surface area, length, size…) in children and adults (Dormal & Pesenti, 2007; Gebuis, Cohen Kadosh, de Haan, & Henik, 2009; Rousselle & Noël, 2008; Rousselle, Palmers, & Noël, 2004). Some studies even fail to find any evidence of a sensitivity to numerical differences when the perceptual variables, which naturally covary with numerosities, are strictly controlled for (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Spelke, 2002; Mix, 2002; Rousselle et al., 2004). Actually, much behavioral and electrophysiological evidence suggests that numerical magnitude processing of large numerosities relies on the integration of multiple perceptual cues (Gebuis, Cohen Kadosh, & Gevers, 2016; Gebuis & Reynvoet, 2012a, 2012b, 2013; Hurewitz, Gelman, & Schnitzer, 2006). With regard to small numerosities, visuo-spatial abilities is also involved in the *subitizing* process, another core ability for later achievement in mathematics (Carey, 2004; Feigenson, Dehaene, & Spelke, 2004; Kahneman, Treisman, & Gibbs, 1992), which allows adults and children to form an exact representation of a small number (up to four visual elements) in a very short time. Basically, subitizing is relying on a process of parallel visuo-spatial tagging with a limited number of spatial indexes (about three or four) coding simultaneously for the position of each object visually presented (Ester, Drew, Klee, Vogel, & Awh, 2012; Piazza, Fumarola, Chinello, & Melcher, 2011; Trick & Pylyshyn, 1994). This process is thus also of particular interest in terms of the link between numerical cognition and visuo-spatial skills.

To sum up, an increasing number of studies highlight that large number representation could be the result of the processing and integration of several other perceptual dimensions such as density, area, rhythm, duration and so on (see Gebuis et al., 2016 for a recent review and an alternative theoretical proposition to the ANS view). Regarding small numerosities, the subitizing process, which leads to the formation of an exact representation of small numbers, also exploits visuo-spatial pre-attentional processing. Together, these results stress

the need to consider the influence of perceptual and visuo-spatial properties on numerical magnitude processing and suggest that visuo-spatial abilities could influence number magnitude processing on at least two levels: (1) at a visuo-perceptual level, in visual tasks requiring participants to process large numerosities disregarding the visuo-perceptual properties of the array, (2) at a pre-attentional level, in visual tasks requiring participants to process small visual numerosities by assigning a limited number of visuo-spatial tags – as is assumed to be the case in subitizing tasks.

One way to address the link between numerical and visual perceptual cognition is to focus on individuals with impaired visuo-spatial skills who are less able to process the visuo-spatial dimensions of visual stimuli (such as area, density, convex hull and so on). If perceptual skills influence large number magnitude processing, people with low visuo-spatial abilities could also demonstrate poor performance in visual number magnitude processing which requires integrating the visuo-spatial dimensions of visual arrays to extract numerosities (such as area, density, convex hull and so on). They should also demonstrate lower subitizing ability in processing small numerosities. On the other hand, these people should perform in the normal range in number magnitude comparison tasks which have no visuo-spatial processing requirement - for instance in the auditory modality (i.e. comparing the numerosities of sequences of sounds).

In this paper, the question of the influence of visuo-spatial processing on basic numerical cognition was addressed by examining the impact of visuo-spatial impairments on number magnitude processing in different modalities with distinct perceptual processing constraints. To that end, we examined a genetic neurodevelopmental disorder which impacts visuo-spatial and mathematical learning abilities, namely, the 22q11.2 deletion syndrome (22q11DS). This genetic condition results from a microdeletion of a series of genes situated at the locus q11.2 on the long arm of one of the two copies of chromosome 22, most of them

occurring de novo (85%; Swillen et al., 1999). It is one of the most common microdeletion syndromes with a prevalence from 1:2000 to 1:6000 (Gothelf, Frisch, Michaelovsky, Weizman, & Shprintzen, 2009). The phenotypic manifestations of this condition are highly variable, including approximately 180 distinct clinical traits. In this population, total IQ is generally in the borderline range (70-79) with half of the individuals scoring in the normal range and the other half exhibiting intellectual disability (i.e. IQ score under 70). Interestingly, it has been repeatedly shown that most people with 22q11DS showed higher verbal than visuo-spatial abilities (Bearden et al., 2001; De Smedt, Devriendt, et al., 2007; Swillen et al., 1997; Woodin et al., 2001). A range of visuo-spatial processing impairments are frequently reported in this syndrome including a deficit in visuo-perceptual and visuo-motor integration skills (Moss et al., 1999; Niklasson & Gillberg, 2010; Van Aken, Caeyenberghs, Smits-Engelsman, & Swillen, 2009) as well as difficulties in visuo-constructive activities such as in puzzles or in tasks requiring the arrangement of blocks or geometric shapes (De Smedt, Swillen, Ghesquière, Devriendt, & Fryns, 2003; Moss et al., 1999; Niklasson & Gillberg, 2010). Moreover, learning disabilities are regularly observed in 22q11DS, with poorer arithmetic than reading (where mainly decoding is impaired) and writing skills (Bearden et al., 2001; De Smedt et al., 2009; Jacobson, 2010).

With regard to their mathematical abilities, all studies highlighted very poor performance in general standardized achievement for children with 22q11DS compared to typically developing children (Moss et al., 1999; Wang, Woodin, Kreps-Falk, & Moss, 2000; Woodin et al., 2001). More in-depth studies provide evidence for poorer calculation abilities compared to control participants matched on age and IQ, especially in calculation tasks requiring the deployment of calculation procedures such as addition and subtraction with a carry, and multi-digit calculations (De Smedt et al., 2009; De Smedt, Reynvoet, Swillen, Verschaffel, & Ghesquière, 2008; De Smedt et al., 2006; De Smedt, Swillen, et al., 2007;

Simon, Bearden, Mc-Ginn, & Zackai, 2005). Furthermore, despite demonstrating preserved

transcoding abilities (De Smedt et al., 2009; De Smedt et al., 2006; De Smedt, Swillen, et al.,

2007) individuals with this disorder often displayed difficulties in the counting range in a dot

numerical estimation task (3-8 dots, Simon et al., 2005; Simon et al., 2008).

The processing of magnitude has been mainly explored in symbolic numerical tasks.

People with 22q11DS were found to present slower reaction times, lower accuracy and

atypical sensitivity to numerical difference when comparing the magnitude of symbolic

numbers (De Smedt et al., 2009; De Smedt, Swillen, et al., 2007; Simon et al., 2005; Simon et

al., 2008). To our knowledge, only one study examined non-symbolic numerical processing

and reported lower numerical acuity in the 22q11DS group while comparing collections of

dots (Oliveira et al., 2014). With regard to non-numerical magnitude, some studies also found

that people with 22q11DS had poorer performance when processing spatial and temporal

continuous dimensions. Compared to age-matched controls, they were slower at comparing

length (Simon et al., 2005; Simon et al., 2008), demonstrated less ability to reproduce

rhythmic patterns as well as less sensitivity to temporal interval differences (Debbané, Glaser,

Gex-Fabry, & Eliez, 2005; Gabriel Mounir, Debbane, Schaer, Glaser, & Eliez, 2011). These

results[1] are consistent with the *Theory of Magnitude* proposed by Walsh (2003) who assumed

the existence of a common metric system for representing number, space and time. In line

with this theoretical framework, some authors have speculated about the existence of a basic

core deficit of magnitude processing in people with 22q11DS. For example, Simon (2008)

claimed that a numerical magnitude processing deficit in 22q11DS would result from a

primitive deficit in processing temporal and spatial magnitude.

---

[1] Some of these results have to be taken cautiously considering methodological issues such as small sample size (N=12, Oliveira et al., 2014) and/or large IQ differences with the control group (Oliveira et al. 2014; Simon 2005).

Finally, subitizing abilities (i.e. the fast and precise apprehension of small numerosities up to three or four) yielded inconsistent results depending on the reference group. The subitizing range has been shown to be reduced in 22q11DS children compared to a control group matched on chronological age (but with more than 30 points' difference in IQ, Simon et al., 2008) while other studies observed a similar subitizing range in 22q11DS children compared to control children who were closer in terms of verbal IQ (De Smedt et al., 2006; 2007).

In sum, very few studies have explored non-symbolic numerical abilities in 22q11DS and most of them have provided inconclusive or inconsistent results. Moreover, all of these studies assessed number magnitude processing in visual tasks which typically require the processing of visuo-spatial cues. As a consequence, it is not possible to determine whether their difficulties result from a deficit of the ANS or from a more general difficulty in the processing visual spatial/perceptual dimensions.

The present study aims at investigating the influence of visuo-spatial abilities on visual magnitude processing by examining people with 22q11 DS, a genetic neurodevelopmental disorder known to affect visuo-spatial and mathematical learning disabilities. Twenty-seven children with 22q11DS were compared to two carefully selected control groups matched either on verbal (verbal control group) or non-verbal estimated IQ (non-verbal control group). A series of non-symbolic magnitude comparison tasks with different visuo-spatial processing requirements (none vs. low vs. high visuo-spatial processing required) and different kinds of magnitude (continuous vs. discrete) were administered. A classical collection comparison was used to assess numerical magnitude processing but, as discussed earlier, this task placed strong emphasis on visuo-spatial processing since stimuli varied in terms of global surface, area and perimeter. Accordingly, a complementary method was used to assess numerical processing using two numerical comparison tasks with sequences of visual and auditory

events (dots or sounds), as used in previous studies (Breukelaar & Dalrymple-Alford, 1998; Dormal, Andres, Dormal, & Pesenti, 2010; Dormal, Seron, & Pesenti, 2006). The dot sequence comparison task minimizes the visuo-spatial load since a single dot is repeatedly flashed at the centre of the screen (visual processing but low spatial demand). The sound sequence comparison task goes one step further with no visual information to be processed, thus ensuring that visual information does not influence numerical magnitude processing in any way. Finally, non-numerical magnitude judgment tasks were administered to examine the hypothesis of a core deficit in magnitude processing and to determine whether the visuo-spatial load interferes only with numerical extraction processes or more globally, with all visuo-spatial magnitude processing. Accordingly, a length comparison task requiring visuo-spatial processing was contrasted with a duration comparison task with no visuo-spatial processing requirement. Finally, a dot estimation task was administered to explore the influence of visuo-spatial skills on subitizing abilities.

Three distinctive patterns of performance were hypothesized. First, an impairment in all magnitude comparison tasks would suggest a generalized magnitude deficit for the processing of number, time and space, in keeping with the Theory of Magnitude proposed by Walsh (2003). A second pattern of result would show an impairment restricted to all numerical tasks (numerical magnitude judgment tasks) and would suggest a number sense deficit in accordance with the ANS view and with previous studies that already showed a less precise magnitude representation for symbolic and non-symbolic numerical stimuli in 22q11DS participants (Oliveira et al., 2014; De Smedt et al, 2007; Simon et al., 2008, 2005). Finally, a deficit restricted to comparison tasks with high visuo-spatial processing demands would attest to the impact of visuo-spatial impairment on general magnitude processing and would add further support to the authors who claim that the extraction of numerosity varies across the mode and modality of presentation of the numerical stimuli. Finally, if subitizing is

dependent on visuo-spatial attentional process (Trick & Pylyshyn, 1994), the apprehension of small quantities should be impaired in the 22q11DS group. As some of our tasks placed high demands on short-term and working memory, these components were examined in order to control for their possible contribution to the results in magnitude comparison tasks. Moreover, mathematical achievement was assessed in all participants in order to examine group differences in mathematical abilities.

METHODS

Participants

Twenty-seven children and adults with the microdeletion 22q11.2 aged between 5 and 23 years old (M = 127.5 months, SD = 49.7 months) and comprising 12 females participated in this study. Participants were recruited through 22q11DS associations and the department of pediatric cardiology of the Saint-Luc University Hospital in Belgium. Diagnosis was confirmed with two-colour fluorescent in situ hybridization (FISH). The 22q11DS group was mainly composed of children from 5 to 12 years-old (N=22) and adolescents from 13 to 17 (N=4) and one adult participant of 23 years-old. As regards participants' academic trajectory, 10 participants were attending schools which provide special needs support while 17 participants were enrolled in mainstream education (see the Appendix for more information about participants with 22q11DS).

Participants with 22q11DS were compared to two control groups: one matched on verbal intelligence and the other on visuo-spatial abilities. The first control group - here labelled as the TD$_{VERBAL}$ group-was composed of 27 typically developing (TD) children (14 girls) aged between 3 and 13 years old (M = 94.6 months, SD = 28.4 months) and individually matched to participants with 22q11DS on verbal intelligence measures using two verbal subtests (Vocabulary and Similarities) from the Wechsler Preschool and Primary Scale of

Intelligence-3rd edition (WIPPSI-III; Wechsler, 2004) or the Wechsler Intelligence Scale for Children-4th edition (WISC-IV; Wechsler, 2005) depending on their age. The second control group – here called the TD_{VSSP} group- included 27 TD children (17 girls) aged between 3 and 12 years old (M = 86.7 months, SD = 30.4 months) and matched to each participant with 22q11DS on their visuo-spatial abilities using the Block design subtest from the WIPPSI-III or the WISC-IV, depending on their age. In both groups, each control participant was paired with one participant with 22q11DS on the basis of the raw score (+/- 4 gap points) obtained in the subtests on which the matching was carried out that is, in the Vocabulary and Similarity subtests in the TD_{VERBAL} group and in the Block design subtest in the TD_{VSSP} group, respectively.

Material

Magnitude comparison tasks

Five magnitude comparison tasks with different visuo-spatial processing requirements (no vs. low vs. high visuo-spatial processing) and presenting different kinds of magnitude (continuous vs. discrete) were administered to participants (see Table 1 for a description). In all tasks, participants had to compare two magnitudes and to select the larger one. All magnitude comparison tasks were carried out on a tablet PC (HP Elitebook 2740p, Screen: 12.1-inch WXGA (1280x800)). Stimuli were presented on a navy blue background using E-Prime experimental software (Version 1.1, Psychology Software Tools, Inc., Pittsburgh, PA). Participants were instructed to touch the screen with a tactile pen on the side of the correct response. The tactile screen was divided by an invisible vertical midline defining two equal response zones, one on the left and the other on the right. Instructions emphasized both speed and accuracy.

Table 1. Description of magnitude comparison tasks.

	No visuo-spatial requirement	Low visuo spatial requirement	High visuo-spatial requirement
Continuous magnitude comparison tasks	Duration comparison		Length comparison
Discrete magnitude comparison tasks	Sound sequence comparison	Dot sequence comparison	Collection comparison

For all magnitude comparison tasks, the difference between the quantities to be compared varied along six different ratios: 1/2, 2/3, 3/4, 5/6, 7/8, 8/9. Two different pairs of magnitudes were presented by ratio. Table 2 presents the pairs of numerosities which were used in the discrete numerical comparison tasks for each ratio. These ratios of increasing complexity were introduced progressively throughout the task to determine individual sensitivity to magnitude difference in each task. Participants always started with stimuli pairs which varied according to the two easiest ratios, that is, 1/2 and 2/3. Less and less discriminable ratios were then progressively introduced (3/4, 5/6, 7/8, and finally 8/9), depending on the participant's correct response rate for each ratio. Pairs of consecutive ratios were always intermixed with each other so that stimulus pairs of one ratio were never presented alone. The task was discontinued when a participant performed at chance level for two out of three consecutive ratios. This procedure was adopted to take into account the participant's individual limits regarding their sensitivity to magnitude differences but also their own attentional capacities. Indeed, presenting participants with so many ratios that they are not able to discriminate could be discouraging. This could lead them to adopt ''guessing'' strategies (Halberda & Feigenson, 2008) which would add a lot a noise to the data, including on easy ratios which could be in fact well discriminated. In each task, the side of the correct response was counterbalanced: each pair appeared four times, twice with the larger magnitude on the right side and twice with the larger magnitude on the left side. When all ratios were presented, participants were administered a total of 48 stimulus pairs in each task (2 pairs x 2

sides x 2 presentations x 6 ratios). Throughout the experiment, pairs were presented in a pseudo-random order (i.e. no identical pairs in two consecutive trials, no more than three consecutive correct responses on the same side and no more than two identical ratios in succession). Before beginning each task, participants performed six practice trials with pairs of magnitudes differing by a 1/3 ratio to check the understanding of the instructions.

Table 2. Pairs of magnitudes presented in non-symbolic magnitude comparison tasks.

	Ratios					
	1/2	2/3	3/4	5/6	7/8	8/9
Small	7-14	6-9	6-8	5-6	7-8	8-9
Large	8-16	10-15	12-16	10-12	14-16	16-18

Continuous magnitude comparison tasks. These tasks, already used in Rousselle et al. (2013), involved no numerical processing and required participants to process the duration or the length of continuous stimuli which were presented in the auditory (no visuo-spatial processing) or in the visual modality (visuo-spatial processing requirement) respectively.

In the *duration comparison task*, participants had to compare the duration of two identical sounds presented successively. Participants had to touch the screen on the side of the ear that ''heard'' the longest sound (from 225 to 1350 ms). In the *length comparison task*, participants had to compare the length of two white lines (the line size varied between 2.3° and 10.3° of visual angle) presented successively and they were instructed to touch the screen on the side of the longest line (see Rousselle et al., 2013 for more details).

Discrete numerical comparison tasks. The three non-symbolic numerical comparison tasks assessed participants' ability to process the discrete numerical properties of sets presented either sequentially (Dot Sequence or Sound Sequence, low- or no-visuo-spatial processing requirement) or simultaneously (Collection, high visuo-spatial processing load).

In the *Sound sequence comparison task*, participants had to compare the numerosities of the two series of tones presented in rapid succession and had to choose the ear that ''heard'' the sequence containing the most sounds by touching the right side of the screen. The stimuli were composed of a sound (audio format: 44100 Hz, 32 bits, Mono) presented rapidly. To prevent participants from basing their judgment on perceptual non-numerical dimensions, the sequences were constructed using non-periodic signals so that temporal ratios did not constitute a potentially confusing variable, and rhythm biases and pattern recognition were avoided (for more details, see Breukelaar & Dalrymple-Alford, 1998; Dormal et al., 2010; Dormal et al., 2006). The durations of the interstimuli interval (ISI) and of the sound presentation time (S) were added within each sequence to obtain the total cumulative duration. The total duration of sequences varied from 1500 ms to 4500 ms while each ISI and S duration varied from 66.7 to 300 ms. The shortest and the longest ISI and S duration were the same within the sequences to be compared (smallest: 66.7 ms, longest: at least 200 ms). Furthermore, numerosity and total duration were manipulated in two congruity conditions. In congruent trials (which represented half of the sample), the larger number of sounds also had the larger total duration while in incongruent trials, the larger number had the smaller total duration. In addition, sound frequency by time unit covaried with numerosity. The trial started with the presentation of two red fixation crosses displayed respectively on the left and right sides of the screen. When the participant was judged to be visually attending to the display, the experimenter triggered the disappearance of the left cross followed by the appearance of the first sequence, on the left. Then, the left fixation cross reappeared and the right cross disappeared and was replaced by the second sequence on the right side of the screen. Instructions emphasized that the duration of the sequence was not important. Participants were instructed not to count the flashed sounds as they would not have the time to do so. They could respond as soon as they had the answer with no time limit after stimuli disappearance.

In the *Dot sequence* comparison task, participants had to compare the numerosities of two sequences of flashed dots presented in rapid succession. The stimulus was a single white dot (diameter: 3.5 cm) flashed rapidly in a single location on the left and then on the right side of the screen. This task was the exact counterpart of the Sound sequence comparison task but in the visual modality, with dots flashed in a single position instead tones. Participants had to touch the screen on the side where more dots had been displayed. They could respond as soon as they had the answer with no time limit after stimuli disappearance.

In the *Collection Comparison task*, participants were asked to compare the numerosities of two collections displayed simultaneously on the screen. Stimuli consisted of two white boxes containing black puzzle pieces. In order to control as much as possible for the influence of perceptual non-numerical dimensions on the participants' judgment, the numerosity and the total cumulated black area and the perimeter were manipulated in two congruity conditions. In congruent trials, the larger array in number was also the one with the larger cumulative black area and the larger density, while in incongruent trials, the larger array in number was the one with the smaller cumulative black area and perimeter. Also, the density covaried with the numerosities. The form of the individual pieces was manipulated so that the variations of cumulative black area were interspersed with those of cumulative individual perimeter (i.e. sum of individual piece perimeters) and brightness. To avoid the larger collection in number being systematically the one with the smaller elements, the area of the smaller and larger pieces was the same in both arrays to be compared. Finally, the convex hull (external perimeter of collections formed by the most external pieces) was equated for all trials. The trial started with the simultaneous presentation of two fixation crosses displayed on the left and right sides of the screen respectively. The two collections were then simultaneously presented on the screen for two seconds, one on the left and the other on the right side of the screen, both covering a visual angle of approximately 24.8°x 9.1°. To answer, participants had

to touch the screen on the side of the box that contained more pieces as soon as they got the answer with no time limit after stimuli disappearance. Instructions emphasized that the size of the pieces was of no importance.

Subitizing task. Participants were briefly presented with arrays of 1 to 7 dots and were asked to say out loud 'how many' dots were presented as quickly and accurately as they could. Stimulus presentation and response recording were carried out on a tablet PC (HP Elitebook 2740p, Screen: 12.1-inch WXGA (1280x800)) using both a voice key (latency recording) and a numerical pad (accuracy measurement). Stimuli were presented on a grey background using E-Prime experimental software (Version 1.1, Psychology Software Tools, Inc., Pittsburgh, PA). Each trial started with the presentation of a central red fixation cross for 500 ms, followed by the display of the target collection of 1 to 7 dots for 200 ms. The collection was then immediately hidden by a mask for 500 ms. Finally, a screen with a question mark was presented until participants gave their response orally. The verbal response triggered a voice key (latencies) and the experimenter then recorded the participant's response on a numerical pad (accuracy). The stimuli consisted of 1 to 7 randomly arranged black dots of equal size (6mm in diameter), plotted randomly in the cells of a 6x6 virtual matrix, comprising the same 5.3x5.3x8 area as the premask. Each numerosity was presented six times in different configurations. The mask consisted of dots of heterogeneous size and covered the whole surface of the screen. The experiment started with seven practice trials.

A control task was administered just before the subitizing task in order to ensure that participants understood the task and perceive the array in such a small time window (200 ms). This control task was exactly the same as the subitizing task but with no numerical processing as the participant simply had to say out loud the color of the dots included in the array which

were either blue, green, yellow or red. As in the subitizing task, arrays were presented 200 ms followed by a mask screen for 500 ms.

Control measures

Mathematical level. To assess mathematical achievement, two kinds of tasks were presented depending on participants' age. Children younger than 7 years old were administered a pictorial additive fluency task while children 7 years and above were assessed using single-digit arithmetic fluency tasks (Rousselle et al., 2013).

The *pictorial additive fluency* task aims to assess first simple additions in preschoolers. This task was used in Rousselle et al. (2013) and adapted from Noël (2009). It includes ten additions presented orally with a pictorial support representing the first operand (e.g., "Look, here are three cows; if three more come, how many cows will there be?"). The set comprised five ties (1+1, 2+2, 3+3, 4+4, 5+5) and five additions with the larger operand presented first (2+1, 3+2, 4+3, 5+4, 6+5). Items were presented in order of increasing complexity with smaller sums presented first and larger sums presented last (sum order: 2, 4, 3, 6, 5, 7, 8, 10, 9 and 11). The participant had 150 seconds to solve a maximum of problems. Each period of five seconds not used to resolve all problems was considered as 1 bonus point added to the total score calculated on the correct response.

Single-digit arithmetic fluencies were also used in Rousselle et al. (2013) and consisted of three tasks involving additions, subtractions and multiplications respectively. For each operation, participants were presented with a sheet of written arithmetic problems and had 150 seconds to solve as many problems as possible (via written response). Addition and multiplication problems were drawn from all possible combinations of the integers 1–9 and the set of subtractions was the exact counterpart of the addition set. These combinations resulted in a total of 81 problems for each operation.

Working memory. The three main components of WM defined in Baddeley and Hitch's model (Baddeley, 1986; Baddeley & Hitch, 1974), namely, the phonological loop, the visuo-spatial sketchpad and the central executive component, were individually examined in tasks that did not require the recall or manipulation of numerical content. Phonological loop capacity was assessed in a forward letter span task. The visuo-spatial sketchpad was assessed with two-dimensional visuo-spatial span tasks inspired by the Corsi Block test. And finally, a category-span task was used to examine the central executive component. The stimuli and procedure used in those tasks have been described extensively in Rousselle et al. (2013).

Experimental procedure

Participants were tested individually in a quiet room. Testing was completed in two approximately 75-minute sessions, depending on participant's performance and attentional level. The first session started with the IQ subtests followed by the three WM subtests. The tasks assessing arithmetic opened the second session and were followed by computerized basic numerical comparison tasks proposed in a Latin square order.

RESULTS

Population description

Table 3 presents the results for age, general cognitive and mathematical measures in the 22q11DS and control groups. Paired-samples t-tests were run to compare each 22q11DS participant to his own verbal and nonverbal-matched control participant. As expected, participants with 22q11DS did not differ from the TD_{VERBAL} group in the two verbal intelligence subtests (vocabulary: $t(26) = -1.68$, $\eta^2 = .10$, $p = .10$; similarities: $t(26) = 1.61$, $\eta^2 = .09$, $p = .12$) and from the TD_{VSSP} group in the block design subtest ($t(26) = -0.47$, $\eta^2 = .00$, $p = .64$), measures on which they were matched (see Table 3). Moreover, the three groups did not significantly differ from each other on the intelligence measures (22q11DS vs. TD_{VSSP} on vocabulary, $t(26) = -0.24$, $\eta^2 = .00$, $p = .81$; 22q11DS vs. TD_{VSSP} on similarities, $t(26) = 1.20$,

$\eta^2 = .05$, $p = .24$; 22q11DS vs. TD$_{VERBAL}$ on block design, $t(26) = -1.79$, $\eta^2 = .11$, $p = .08$).

Finally, the 22q11DS group differed marginally from the TD$_{VERBAL}$ group ($t(26) = -2.06$, $\eta^2 = .14$, $p = .05$) but not from the TD$_{VSSP}$ group ($t(26) = 1.19$, $\eta^2 = .05$, $p = .24$) on the concept identification subtest (i.e. the reasoning test which was presented visually). However, paired-samples t-tests revealed significant differences between groups on age, the 22q11DS participants being older than the TD$_{VERBAL}$ group which itself was older than the TD$_{VSSP}$ group, as detailed in the Method section (all ts $(26) > 4.18$, all $\eta^2 > .40$, ps $<.001$).

In order to estimate the severity of difficulties of the 22q11DS group, raw scores of each measure were converted into standard scores using the norms provided by the Wechsler scales (three older participants were compared to the higher level of age for the test). The mean of the standard score in the 22q11DS group for the vocabulary subtest was 5.69 ± 2.59 (range from 1 to 11), 7.74 ± 3.43 (range from 1 to 13) for the similarities subtest, 5.52 ± 3.30 (range from 1 to 12) for the block design subtest and 6.63 ± 3.26 (range from 1 to 13) for the concept identification subtest. In this population authors have usually observed better performance for nonverbal than verbal IQ (Chow, Watson, Young, & Bassett, 2006; Swillen et al., 1999; Woodin et al., 2001). However recent studies tend to show that this difference is quite small and in some cases, the reverse profile has been observed (De Smedt et al., 2007; 2009; Simon et al., 2007). In line with this, the mean standard scores for the verbal subtests (i.e. vocabulary and similarities subtests) were slightly higher than those of the block design subtest for most 22q11DS participants (i.e. 13 participants had 2 to 6 points more on average). Only three participants presented the reverse profile (visuo-spatial higher than verbal mean standard score) and eleven participants showed no significant difference between these two scores (between -1 to 1 point). With regard to the control participants, the TD$_{VERBAL}$ group achieved standard scores in the mean for each subtest (vocabulary: 9.89 ± 1.65; similarities: 10.63 ± 1.57; block design: 9.78 ± 1.65; concept identification: 10.63 ± 2.26) as the TD$_{VSSP}$

group[2] (vocabulary: 11.3. ± 2.41; similarities: 11.25 ± 3.19; block design: 9.40 ± 1.47; concept identification: 9.85 ± 1.98).

Memory abilities

At a general cognitive level (see Table 3), paired-samples t-tests showed no significant differences between groups on STM measures (visuo-spatial or verbal), or on the verbal WM measure (all Ts (26) <1.40, all η^2 < .07, ps >.05). However, it is important to note that the 22q11DS group performed slightly lower than the TD$_{VERBAL}$ group on the visuo-spatial STM measure (t(26) = -1.86, η^2 = .12, p =.07) but obtained similar scores in the verbal STM task, while the reverse pattern was true compared to the TD$_{VSSP}$ group.

Table 3. Data and paired t-tests for general measures in 22q11DS, verbal and visuo-spatial control groups.

	22q11DS		TD$_{VERBAL}$		TD$_{VSSP}$	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Age	127.52	49.69	94.59***	28.38	86.74***	30.44
IQ measures (raw score)						
Vocabulary	22.44	7.78	23.63	8.25	23.00	10.52
Similarities	18	5.88	17.04	5.32	15.63	8.65
Block design	25.19	10.64	29.19	9.64	25.37	10.54
Concept identification	14.48	3.83	15.93	3.32	13.15	4.64
Working memory						
Visuo-spatial sketchpad	4.48	1.67	5.11	1.63	4.19	1.44
Phonological loop	6.04	2.01	6.04	1.43	5.67	1.57
Central executive	5.00	2.22	5.26	1.70	4.96	1.74
Mathematical fluency						
Pictorial additive fluency	8.00	6.13	11.27 [a]	5.71	10.82 [a]	6.29
Pictorial additive fluency (errors)	4.45	3.33	1.00 [a] *	1.55	2.00 [a] *	1.90
Addition fluency	24.93	13.19	19.07 [b]	10.96	20.60 [c]	7.37
Subtraction fluency	19.40	11.35	16.27 [b]	9.96	19.60 [c]	6.33

---

[2] This analysis included only 20 participants since the IQ of 7 control children was assessed with a scale not suitable to their age, the standard score thus being unavailable.

Multiplication fluency	18.80	12.62	12.60 [b]	9.65	16.90 [c]	11.29

[a] N=11, [b] N=15, [c] N=10; * p < .05, *** p < .001

Mathematical abilities

With regard to the mathematical achievement levels for young children (N = 11), there was no significant difference between the three groups on the number of problems solved correctly (for 22q11DS vs. TD_{VERBAL} groups, t(10) = -1.66, η^2 = .21, p = .13; for 22q11DS vs. TD_{VSSP} groups, t(10) = -1.49, η^2 = .18, p = .16). With regard to the number of errors produced in the Pictorial additive fluency task, the 22q11DS group differed significantly from both control groups (22q11DS vs. TD_{VERBAL}: t(10) = 3.02, η^2 = .48, p < .05; 22q11DS vs. TD_{VSSP}: t(10) = 2.32, η^2 = .35, p < .05), their performance in simple addition being more error-prone (see Table 3).

Regarding the older participants who performed the single-digit arithmetic fluencies, we did not observe significant differences between 22q11DS and both control groups (all ts < 1.67, ps> .11). The 22q11DS group actually presented better performance than the two other groups since they were older and were generally in higher-level school classes than the control groups.

Magnitude representation tasks

To investigate the precision of the underlying non-symbolic magnitude representations, analyses were carried out on the Weber fractions (following Pica et al., 2004 and Halberda and Feigenson, 2008, see Supplement S1 of Rousselle et al., 2013 for an extensive description of the Weber fraction estimation method). The Weber fraction is a reliable index of a participant's sensitivity to magnitude difference and reflects the variation of performance as a function of the ratio between the magnitudes to be compared. Moreover, the Weber fraction was more robust than accuracy as our tasks were adaptative and consequently, all participants did not necessarily achieve the same number of items. Paired t-tests on Weber fractions showed a specific deficit for the length comparison task: the

22q11DS group in fact presented higher Weber fractions, indicating lower precision of the underlying magnitude representation than both control groups (22q11DS vs. TD$_{VERBAL}$ groups, t(26) = 2.72, η^2 = .22, p < .01; 22q11DS vs. TD$_{VSSP}$ groups, t(26) = 2.52, η^2 = .20, p < .05). However, no such difference appeared in the comparison of the duration of auditory stimuli (22q11DS vs. TD$_{VERBAL}$ groups: t(26) = 0.93, η^2 = .03, p = .46 and 22q11DS vs. TD$_{VSSP}$ groups: t(26) = 0.07, η^2 = .00, p = .94).

Regarding discrete numerical magnitude processing, only the representation of magnitude in the collection comparison task was impaired, with a significantly higher Weber fraction in the 22q11DS group compared to the TD$_{VERBAL}$ group (t(26) = 3.12, η^2 = .27, p < .01) but a marginally significant difference compared to the TD$_{VSSP}$ group (t(26) = 1.96, η^2 = .13, p = .06). Moreover, as we can see in Figure 1, the Weber fraction did not differ between the three groups in both sequential tasks, whether stimuli were visual or auditory (all ts <.90, ps >.38) [3]. In sum, these first results indicate a specific deficit in magnitude comparison tasks requiring more visuo-spatial processing, regardless of the kind of magnitude processing involved, whether for continuous or discrete stimuli.

Figure 1. Mean and the standard error of Weber fractions in the magnitude comparison tasks for the three groups.

---

[3] The same analyses conducted on a subsample of patients with 22q11DS with a restricted age range (22 participants with 22q11DS aged from 5 to 12 years old) confirmed the results obtained with the initial group (including adolescents and one adult) by showing globally a specific deficit in both continuous and discrete magnitude when visuo-spatial processing requirement is higher.
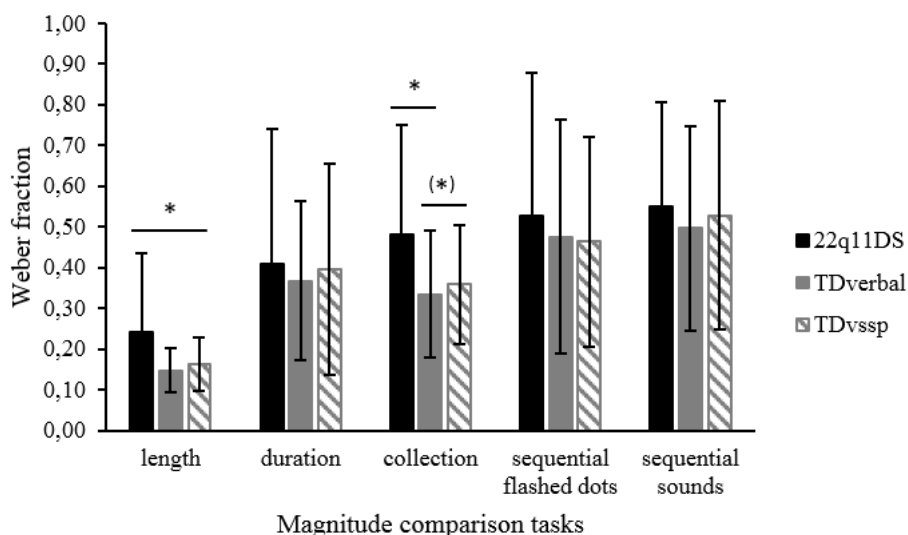
In order to determine the extent to which the visuo-spatial abilities interact with the extraction of numerosities, analyses were run to examine the effect of congruency on the three non-symbolic number comparison tasks. We predicted that the congruency effect would be reduced in children and adolescents with 22q11DS. Indeed, given their visuo-spatial impairments, they could be less sensitive to perceptual variations. Consequently, these variations would be less likely to interfere with or facilitate the processing of numerosity in the incongruent and congruent conditions, respectively. To examine the congruency effect, accuracy was computed separately for congruent and incongruent trials in each group. Accuracy for congruent and incongruent trials was calculated on the basis of performance on the 1/2 and 2/3 ratios, which were the only ratios that were systematically administered to all participants. The congruency effect was then computed as the difference between the percentage of correct responses for congruent and incongruent trials. Paired samples t-tests were conducted to investigate group differences on this congruency effect in the three non-symbolic numerical comparison tasks. Our analyses showed no significant group differences in the collection comparison task nor in the sequential comparison tasks (all ts < 1.23, ps > .23).

Subitizing

For each individual, the subitizing range was determined by considering the larger numerosity for which at least 5 out of the 6 trials had led to correct responses. We assumed that the 22q11DS group would be impaired in the subitzing range, which is dependent on visual cues and/or on visual attention processes. One 22q11DS participant could not complete the subitizing task because of technical problems and six participants with 22q11DS were unable to undertake the control task (color judgment) due to defective experimental material. We therefore considered only the 20 participants who were administered both the subitizing and the control task. It should be noted that they all succeeded in the control task (all participants performed higher than 75 % with a mean of 97,7 % of accuracy). In the control tasks paired t-tests showed no difference between the 22q11DS and the TD_{VERBAL} groups ($t(19) = -1.75$, $\eta^2 = .14$, $p = .10$) nor between the 22q11DS and the TD_{VSSP} groups ($t(19) = -1.23$, $\eta^2 = .07$, $p = .23$). With regard to the subitizing task, paired-samples t-tests showed a significantly reduced subitizing range for the 22q11DS group (2.70 ± 1.98) in comparison with the TD_{VERBAL} group (3.75 ± 1.07) ($t(19) = -3.05$, $\eta^2 = .33$, $p < .01$) but not when compared to the TD_{VSSP} group (2.90 ± 1.33) ($t(19) = -0.38$, $\eta^2 = .01$, $p = .71$).

Figure 2. Accuracy for the different numerosities in the three groups.
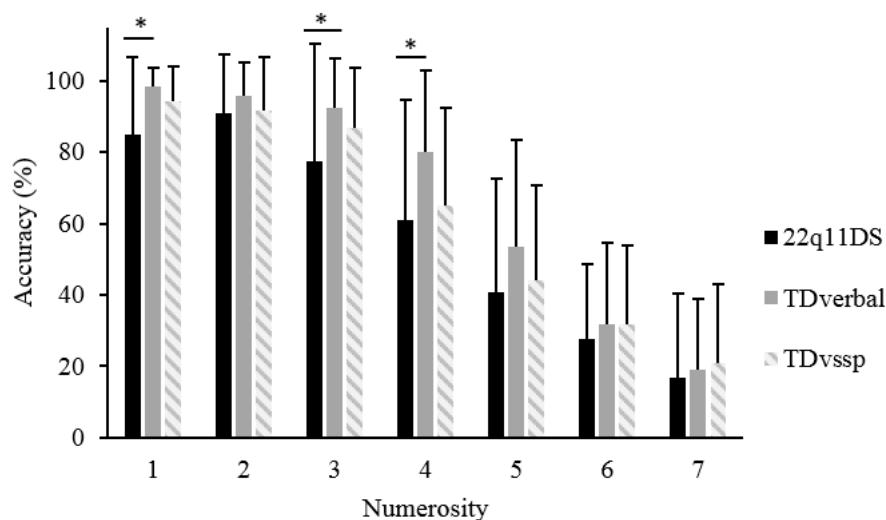
In order to investiagate group differences, paired-samples t-tests were run to compare groups on each quantity within the subitizing range (generally considered from 1 to 3) and

within the counting range (from 4 to 7 in this task). Theses analyses showed significant differences between the 22q11DS group and the TD_{VERBAL} group for the four first numerosities (all ts > 2.48, ps < .02) with the exception of the numerosity 2 (t(19) = -1.30, p = .21) but not for the three last numerosities (all ts < 1.39, ps > .18). With regard to the TD_{VSSP} group, the 22q11DS group did not differ significantly for the numerosity in the subitzing or counting range (all ts < 1.64, ps > .12) [4].

DISCUSSION

The main purpose of this research was to investigate the influence of visuo-spatial skills on numerical magnitude processing. According to the ANS view, number magnitude representation is constructed by disregarding perceptual dimensions. Thus, the acuity of the ANS should be similar whatever the modality or mode of presentation of the stimuli and should not be affected by low visuo-spatial skills. On the other hand, another line of evidence suggests that numerical acuity could vary across tasks depending on the modality or mode of presentation of the stimuli. According to this view, poor abilities in processing visuo-spatial dimension can impact the acuity of numerical representations in the visual modality and especially in tasks with high visuo-spatial processing requirements. Moreover, as subitizing abilities are assumed to rely on visuo-spatial attentional processes and visuo-spatial working memory, low visuo-spatial skills were also expected to reduce the subitizing range (Ester et al., 2012; Piazza et al., 2011; Trick & Pylyshyn, 1994).

The present study aims at contrasting these views by examining magnitude representation in people with 22q11DS, a genetic condition characterized by a frequent

---

[4] The analyses on the 26 participants with 22q11DS administered the subitizing task only showed globally the same significant differences between the 22q11DS group and the TD_{VERBAL} group for the four first numerosities (all ts > 2.30, ps < .03) but not for the three last numerosities (all ts < 1.08, ps > .29). With regards to the TD_{VSSP} group, the 22q11DS group differed significantly only for the numerosity one and three (all ts > 2.28, ps < .03), but not for the numerosity two or within the counting range (4 to 7, all ts < 1.58, ps > .13).

association of visuo-spatial impairment and mathematical learning disabilities. A series of magnitude judgment tasks contrasting different visuo-spatial processing requirements (no vs. low vs. high visuo-spatial processing), with different kinds of magnitude processing (continuous vs. discrete non-symbolic magnitude), were administered to a group of participants with 22q11DS and to two control groups matched on verbal or visuo-spatial abilities, respectively.

In the non-numerical magnitude tasks, results revealed that people with 22q11DS exhibited a specific deficit in processing length but showed unimpaired acuity while processing durations relative to both control groups. This dissociation suggests a specific alteration of visuo-spatial magnitude processing. In the number magnitude comparison tasks, participants with 22q11DS exhibited a significantly lower precision than the verbal control group when they were asked to simultaneously compare the numerosities of two arrays of stimuli. By contrast, these differences were no longer significant when they had to compare the numerosities of sequences of dots or sounds, that is, tasks involving no or low visuo-spatial processing. Finally, the subitizing range was reduced in participants with 22q11DS compared to the verbal control group resulting in lower achievement in numerical estimation within the subitizing range, relative to the verbal control group.

These results are consistent with recent findings in people with 22q11DS, highlighting both a deficit of continuous visual quantities (length comparison task, Simon et al., 2005) as well as a deficit in non-symbolic number magnitude processing as reported in a numerical collection comparison task (Oliveira et al., 2014). As previous studies compared performance of the 22q11DS group to those of a control group matched on chronological age, the present results add to the existing literature, confirming the existence of these deficits when comparing 22q11DS participants to verbal IQ matched control participants. With regard to duration judgement, our results are inconsistent with previous data showing temporal

perception impairment in people with 22q11DS (Debbané et al., 2005; Gabriel Mounir et al., 2011). However, in those experiments, different methodological choices were made in order to measure the least significant difference that the participant could subjectively perceive, which could account for our divergent results.

Our study sheds new lights on the current literature by demonstrating that this deficit is restricted to magnitude comparison tasks with high visuo-spatial processing load. In fact, performance was in the range of TD children on several tasks with minimal visuo-spatial processing requirements, for instance, when comparing the numerosity of auditory or visual stimuli presented in sequence or when comparing duration. Our data in patients with 22q11DS indicates that they do not present a defective ANS but rather a deficit in building numerical representation in high-demanding visuo-spatial processing conditions. Poorer visuo-spatial processing experience accumulates, leading to poorer precision of the resulting number magnitude representation compared to typically developing children who can count on appropriate visuo-spatial experiences.

This study confirms and strengthens findings reported in other genetic syndromes with poor visuo-spatial abilities. For example, individuals with Williams syndrome also showed lower performance in numerical and spatial magnitude comparison tasks in comparison with a control group matched on verbal IQ, suggesting a direct influence of visuo-spatial deficit on magnitude processing (Rousselle et al., 2013). Moreover, individuals with low visuo-spatial skills but with no associated genetic disorder were found to show atypical number magnitude representation, at least when measured in some specific conditions (Bachot et al., 2005; Crollen & Noël, 2015).

In summary, the present study provides evidence of (1) poorer numerical acuity in numerical comparison tasks which have high visuo-spatial demands but not in the other numerical comparisons, (2) lower skills in processing length but not duration, (3) and a

reduced ability to quickly extract numerosities in the subitizing range in participants with 22q11DS. Taken together, these findings call into question the construction of an amodal numerical representation, as posited by the ANS model. Rather, it suggests that the numerical magnitude representation resulting from non-symbolic numerical processing are highly dependent on the perceptual demands of the numerical task at hand. This does not preclude that the resulting magnitude representation could be compared across modality but current models should now take into account the influence of perceptual processing in the sequence of steps leading to the extraction of numerical magnitude information.

Our results thus add to the large body of evidence showing that processing visuo-perceptual dimensions is part of the construction of number magnitude representations. Of course, it is misleading to think that number magnitude acuity could be measured in a "pure" way, i.e., independently of non-numerical perceptual dimensions. For instance, it has been shown that 3 year-old children performed at random on a numerosity judgment task in conditions that controlled for surface area, indicating that their "numerical" judgment is based on surface processing (Rousselle et al., 2004). Later on, the influence of parallel surface processing decreases (Rousselle & Noël, 2008) but even adults continue to be sensitive to perceptual dimensions in their numerical judgments (Gebuis & Reynvoet, 2012a, 2012b; Szucs, Nobes, Devine, Gabriel, & Gebuis, 2013). Even if the majority of studies currently try to control the influence of perceptual variables when assessing non-symbolic magnitude processing (Halberda & Feigenson, 2008; Halberda, Mazzocco, & Feigenson, 2008; Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004), the visual stimulus properties (e.g., surface, density) cannot be controlled for in each individual trial (Gebuis & Reynvoet, 2011, 2012a).

In this study, a deficit of subitizing abilities was also expected, considering that these are assumed to rely on visuo-spatial attentional processes and visuo-spatial working memory,

(Ester et al., 2012; Piazza et al., 2011; Trick & Pylyshyn, 1994). However, other authors consider that subitizing does not depend that heavily on visuo-attentional processes (Piazza, Mechelli, Butterworth, & Price, 2002; Sathian et al., 1999). Our results are in line with the idea that subitizing ability operates under the direct influence of visuo-spatial processes. In this respect, the current literature has yielded inconsistent results, with some studies indicating impaired subitizing abilities in children with 22q11DS (Simon et al., 2005) while others reported no such deficit compared to a control group matched on chronological age (Simon et al., 2008; De Smedt et al., 2006; 2007). Here, subitizing abilities of participants with 22q11DS were found to be impaired compared to a control group matched on verbal IQ, as attested by their reduced subitizing range (around 3 vs. 4 for the control group) and their lower precision in apprehending small numerosities from 1 to 4. Several methodological limitations could explain the contradictory results reported in previous studies: First, some studies had very small sample sizes (N<15 in De Smedt et al.'s studies); second, the timing of the stimulus presentation was often unlimited whereas, in the present study, collections were presented for a very short duration (200 ms) and were followed by a mask to clearly prevent any attempt of counting; finally, other studies chose to compare participants with 22q11DS to controls matched on chronological age only. As IQ differences between groups were not properly controlled for, the source of the difficulties could not be clearly established (even if De Smedt et al., 2006, 2007 used IQ performance as a covariate).

Although this study was run mainly on children, one limit is that it fails to adopt a developmental approach. With regard to the relationship between perceptual and numerical cognition, it make sense to consider that visuo-spatial and temporal processing are necessary for a truly abstract numerical representation to emerge in the course of development (Bueti & Walsh, 2009; Simon, 2008; Walsh, 2003). These basic processing abilities may be determinant for numerical processing development during early childhood but may no longer

play a role later during adolescence or adulthood. The only way to address this issue in a truly developmental perspective is to examine the full developmental trajectories of basic numerical processing in atypical develpment to assess how the pattern of performance changes progressively from early childhood onwards and more particularly, how the changes in visuo-spatial and temporal perception interact with numerical ontogenesis at different times across development. Another limitation is that we did not collect information about the presence of effective mathematical learning impairment in our sample of patients while it is known that all people with 22q11DS do not struggle with mathematical learning by the time of their schooling. Here, comparing mathematical abilities across groups tells us that people with 22q11DS had lower mathematical achievement as a group compared to their verbal-matched typically developing peers but it does not reveal anything about how their deficit in basic numerical cognition has influenced their formal learning of mathematics. Again, longitudinal studies, especially in genetic syndromes associated with a higher risk of mathematical learning disabilities, would be helpful to determine how differences in these basic magnitude processing predict later outcomes in mathematics.

To conclude, the present findings further indicate that magnitude processing is deeply rooted in our ability to process perceptual dimensions. Number magnitude representation is typically assessed using collection comparison tasks. However, this study demonstrated that performance in this type of task is clearly influenced by visuo-spatial abilities. Indeed, the deficit observed in non-symbolic magnitude representation in the 22q11DS population was mainly due to their visuo-spatial processing impairments as it was observed only in the tasks that loaded heavily on this dimension. These results thus highlight the importance of examining magnitude representation with non-visual tasks, especially in children with low visuo-spatial skills, as the influence of visual variables cannot be completely ruled out in numerosity processing.

ACKNOWLEDGMENTS

REFERENCES

Baddeley, A. D. (1986). *Working memory*. Oxford, England: Oxford University Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (pp. 47-90). San Diego, CA: Academic Press.

Barth, H., Kanwisher, N., & Spelke, E. (2003). The construction of large number representations in adults. *Cognition, 86*(3), 201-221.

Barth, H., La Mont, K., Lipton, J., Dehaene, S., Kanwisher, N., & Spelke, E. (2006). Non-symbolic arithmetic in adults and young children. *Cognition, 98*(3), 199-222.

Bearden, C. E., Woodin, M. F., Wang, P. P., Moss, E., McDonald-McGinn, D., Zackai, E., . . . Cannon, T. D. (2001). The neurocognitive phenotype of the 22q11. 2 deletion syndrome: selective deficit in visual-spatial memory. *Journal of Clinical and Experimental Neuropsychology, 23*(4), 447-464.

Breukelaar, J. W., & Dalrymple-Alford, J. C. (1998). Timing ability and numerical competence in rats. *Journal of Experimental Psychology: Animal Behavior Processes, 24*(1), 84.

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1525), 1831-1840. doi:10.1098/rstb.2009.0028

Carey, S. (2004). Bootstrapping & the origin of concepts. *Daedalus, 133*(1), 59-68. doi:doi:10.1162/001152604772746701

Chow, E. W., Watson, M., Young, D. A., & Bassett, A. S. (2006). Neurocognitive profile in 22q11 deletion syndrome and schizophrenia. *Schizophrenia research, 87*(1), 270-278.

Clearfield, M. W., & Mix, K. S. (1999). Number versus contour length in infants' discrimination of small visual sets. *Psychological Science, 10*(5), 408-411.

Clearfield, M. W., & Mix, K. S. (2001). Amount versus number: Infants' use of area and contour length to discriminate small sets. *Journal of Cognition and Development, 2*(3), 243-260.

De Smedt, B., Devriendt, K., Fryns, J. P., Vogels, A., Gewillig, M., & Swillen, A. (2007). Intellectual abilities in a large sample of children with Velo–Cardio–facial syndrome: An update. *Journal of Intellectual Disability Research, 51*(9), 666-670.

De Smedt, B., Reynvoet, B., Swillen, A., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Basic number processing and difficulties in single-digit arithmetic: Evidence from Velo-Cardio-Facial Syndrome. *cortex, 45*(2), 177-188.

De Smedt, B., Reynvoet, B., Swillen, A., Verschaffel, L., & Ghesquière, P. (2008). *Basic number processing and dyscalculia in children with velocardiofacial syndrome (22q11deletion syndrome).* Paper presented at the International Journal of Psychology.

De Smedt, B., Swillen, A., Devriendt, K., Fryns, J.-P., Verschaffel, L., & Ghesquiere, P. (2006). Mathematical disabilities in young primary school children with velo-cardio-facial syndrome. *Genetic Counseling, 17*(3), 259-280.

De Smedt, B., Swillen, A., Devriendt, K., Fryns, J.-P., Verschaffel, L., & Ghesquière, P. (2007). Mathematical disabilities in children with velo-cardio-facial syndrome. *Neuropsychologia, 45*(5), 885-895.

De Smedt, B., Swillen, A., Ghesquière, P., Devriendt, K., & Fryns, J.-P. (2003). Pre-academic and early academic achievement in children with velocardiofacial syndrome (del22q11. 2) of borderline or normal intelligence. *Genetic Counselling, 14*(1), 15-30.

Debbané, M., Glaser, B., Gex-Fabry, M., & Eliez, S. (2005). Temporal perception in velo-cardio-facial syndrome. *Neuropsychologia, 43*(12), 1754-1762. doi:http://dx.doi.org/10.1016/j.neuropsychologia.2005.02.006

Dehaene, S., & Changeux, J.-P. (1993). Development of elementary numerical abilities: A neuronal model. *Journal of Cognitive Neuroscience, 5*(4), 390-407.

Dormal, V., Andres, M., Dormal, G., & Pesenti, M. (2010). Mode-dependent and mode-independent representations of numerosity in the right intraparietal sulcus. *NeuroImage, 52*(4), 1677-1686. doi:DOI: 10.1016/j.neuroimage.2010.04.254

Dormal, V., & Pesenti, M. (2007). Numerosity-length interference: A Stroop experiment. *Experimental Psychology, 54*(4), 289-297.

Dormal, V., Seron, X., & Pesenti, M. (2006). Numerosity-duration interference: A Stroop experiment. *Acta psychologica, 121*(2), 109-124.

Ester, E. F., Drew, T., Klee, D., Vogel, E. K., & Awh, E. (2012). Neural measures reveal a fixed item limit in subitizing. *The Journal of Neuroscience, 32*(21), 7169-7177.

Feigenson, L., Carey, S., & Spelke, E. (2002). Infants' discrimination of number vs. continuous extent. *Cognitive Psychology, 44*(1), 33-66.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences, 8*(7), 307-314.

Féron, J., Gentaz, E., & Streri, A. (2006). Evidence of amodal representation of small numbers across visuo-tactile modalities in 5-month-old infants. *Cognitive Development, 21*(2), 81-92.

Gabriel Mounir, D., Debbane, M., Schaer, M., Glaser, B., & Eliez, S. (2011). [Time processing in the velo-cardio-facial syndrome (22q11) and its link with the caudate nucleus]. *Encephale, 37 Suppl 1*, S42-49. doi:10.1016/j.encep.2010.04.011

Gebuis, T., Cohen Kadosh, R., de Haan, E., & Henik, A. (2009). Automatic quantity processing in 5-year olds and adults. *Cognitive Processing, 10*(2), 133-142.

Gebuis, T., Cohen Kadosh, R., & Gevers, W. (2016). Sensory-integration system rather than approximate number system underlies numerosity processing: A critical review. *Acta psychologica, 171*, 17-35.

Gebuis, T., & Reynvoet, B. (2011). Generating nonsymbolic number stimuli. *Behavior research methods, 43*(4), 981-986.

Gebuis, T., & Reynvoet, B. (2012a). The interplay between nonsymbolic number and its continuous visual properties. *Journal of Experimental Psychology: General, 141*(4), 642.

Gebuis, T., & Reynvoet, B. (2012b). The role of visual information in numerosity estimation. *PLoS ONE, 7*(5), e37426.

Gebuis, T., & Reynvoet, B. (2013). The neural mechanisms underlying passive and active processing of numerosity. *Neuroimage, 70*, 301-307. doi:10.1016/j.neuroimage.2012.12.048

Gothelf, D., Frisch, A., Michaelovsky, E., Weizman, A., & Shprintzen, R. J. (2009). Velocardiofacial syndrome. *Journal of mental health research in intellectual disabilities, 2*(2), 149-167.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the" number sense": The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology, 44*(5), 1457-1465.

Halberda, J., Mazzocco, M. M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature, 455*(7213), 665-668.

Hurewitz, F., Gelman, R., & Schnitzer, B. (2006). Sometimes area counts more than number. *Proceedings of the National Academy of Sciences, 103*(51), 19599-19604.

Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences, 106*(25), 10382-10385.

Jacobson, D. (2010). Substrates of Social Functioning in Individuals with VCFS.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology, 24*(2), 175-219.

Kobayashi, T., Hiraki, K., & Hasegawa, T. (2005). Auditory-visual intermodal matching of small numerosities in 6-month-old infants. *Developmental Science, 8*(5), 409-419.

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child development, 82*(4), 1224-1237.

Meck, W. H., & Church, R. M. (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology: Animal Behavior Processes, 9*(3), 320-334.

Mix, K. S. (2002). The construction of number concepts. *Cognitive Development, 17*(3), 1345-1363.

Moss, E. M., Batshaw, M. L., Solot, C. B., Gerdes, M., McDonald-McGinn, D. M., Driscoll, D. A., . . . Wang, P. P. (1999). Psychoeducational profile of the 22q11. 2 microdeletion: a complex pattern. *The journal of Pediatrics, 134*(2), 193-198.

Niklasson, L., & Gillberg, C. (2010). The neuropsychology of 22q11 deletion syndrome. A neuropsychiatric study of 100 individuals. *Research In Developmental Disabilities, 31*(1), 185-194.

Oliveira, L. F. S., Santos, A. O., Vianna, G. S., Ninno, C. Q. M. S. D., Giacheti, C. M., Carvalho, M. R. S., . . . Haase, V. G. (2014). Impaired acuity of the approximate number system in 22q11.2 microdeletion syndrome. *Psychology & Neuroscience, 7*, 151-158.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., . . . Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition, 116*(1), 33-41.

Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition, 121*(1), 147-153.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron, 44*(3), 547-555.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. J. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage, 15*(2), 435-446.

Rousselle, L., Dembour, G., & Noël, M.-P. (2013). Magnitude Representations in Williams Syndrome: Differential Acuity in Time, Space and Number Processing. *PLoS ONE, 8*(8), e72621. doi:10.1371/journal.pone.0072621

Rousselle, L., & Noël, M.-P. (2008). The development of automatic numerosity processing in preschoolers: Evidence for numerosity-perceptual interference. *Developmental Psychology, 44*(2), 544-560. doi:10.1037/0012-1649.44.2.544

Rousselle, L., Palmers, E., & Noël, M.-P. (2004). Magnitude comparison in preschoolers: What counts? Influence of perceptual variables. *Journal of Experimental Child Psychology, 87*(1), 57-84.

Sathian, K., Simon, T. J., Peterson, S., Patel, G. A., Hoffman, J. M., & Grafton, S. T. (1999). Neural evidence linking visual object enumeration and attention. *Journal of Cognitive Neuroscience, 11*(1), 36-51.

Simon, T. J. (2008). A new account of the neurocognitive foundations of impairments in space, time and number processing in children with chromosome 22q11.2 deletion syndrome. *Developmental Disabilities Research Reviews, 14*, 52-58.

Simon, T. J., Bearden, C. E., Mc-Ginn, D. M., & Zackai, E. (2005). Visuospatial and numerical cognitive deficits in children with chromosome 22q11. 2 deletion syndrome. *Cortex, 41*(2), 145-155.

Simon, T. J., Takarae, Y., DeBoer, T., McDonald-McGinn, D., Zackai, E., & Ross, J. (2008). Overlapping numerical cognition impairments in children with chromosome 22q11. 2 deletion or Turner syndromes. *Neuropsychologia, 46*(1), 82-94. doi:10.1016/j.neuropsychologia.2007.08.016

Swillen, A., Devriendt, K., Legius, E., Eyskens, B., Dumoulin, M., Gewillig, M., & Fryns, J.-P. (1997). Intelligence and psychosocial adjustment in velocardiofacial syndrome: a study of 37 children and adolescents with VCFS. *Journal of Medical Genetics, 34*(6), 453-458.

Swillen, A., Vandeputte, L., Cracco, J., Maes, B., Ghesquière, P., Devriendt, K., & Fryns, J.-P. (1999). Neuropsychological, learning and psychosocial profile of primary school aged children with the velo-cardio-facial syndrome (22q11 deletion): evidence for a nonverbal learning disability? *Child Neuropsychology, 5*(4), 230-241.

Szucs, D., Nobes, A., Devine, A., Gabriel, F., & Gebuis, T. (2013). Visual stimulus parameters seriously compromise the measurement of approximate number system acuity and comparative effects between adults and children. *Frontiers in Psychology, 4*, 444.

Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological review, 101*(1), 80-102.

Van Aken, K., Caeyenberghs, K., Smits-Engelsman, B., & Swillen, A. (2009). The motor profile of primary school-age children with a 22q11. 2 deletion syndrome (22q11. 2DS) and an age-and IQ-matched control group. *Child Neuropsychology, 15*(6), 532-542.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*(11), 483-488.

Wang, P. P., Woodin, M. F., Kreps-Falk, R., & Moss, E. M. (2000). Research on behavioral phenotypes: velocardiofacial syndrome (deletion 22q11. 2). *Developmental Medicine & Child Neurology, 42*(6), 422-427.

Woodin, M., Wang, P. P., Aleman, D., McDonald-McGinn, D., Zackai, E., & Moss, E.

(2001). Neuropsychological profile of children and adolescents with the 22q11. 2

microdeletion. *Genetics in Medicine, 3*(1), 34-39.