The Spanish Journal of Psychology
2011, Vol. 14 No. 1, 50-61
doi:10.5209/rev_SJOP.2011.v14.n1.4

Copyright 2011 by The Spanish Journal of Psychology
ISSN 1138-7416

Typical Development of Quantity Comparison in School-Aged Children

Danilka Castro Cañizares[1], Nancy Estévez Pérez[1], and Otmara Pérez Marrero[2]

[1]Centro de Neurociencias de Cuba (Cuba)
[2]Universidad de la Habana (Cuba)

Although basic numerical skills have been widely studied in the last years, very few studies have undertaken a developmental approach. The present study evaluated the development of the magnitude comparison basic numerical ability, in children from first, third and sixth grades by means of the subject's response time in numerical tasks presented in symbolic and non-symbolic formats. The results showed a significant decrease on quantities processing speed as age increases, which suggests numerical skills tend to become automatic with instruction. The differences found, concerning the general achievement pattern in each school year, might express the maturational specificities of the numerical representation system through development.
Keywords: development, distance effect, magnitude comparison, presentation format.

Aunque las capacidades numéricas básicas han sido ampliamente investigadas en los últimos años, muy pocos estudios han tenido en cuenta una perspectiva del desarrollo de las mismas. En este estudio se evaluó el desarrollo de la capacidad numérica básica de comparación de cantidades en escolares de primero, tercero y sexto grados, a través del análisis del tiempo de reacción de los sujetos en tareas numéricas presentadas en formatos simbólico y no simbólico. Los resultados mostraron una disminución significativa en la velocidad de procesamiento de las cantidades con el incremento de la edad, lo cual apunta a una automatización de las habilidades numéricas con el aumento del nivel escolar. Las diferencias encontradas en el patrón de rendimiento general en cada grado escolar podrían expresar las particularidades de la maduración del sistema de representación numérica en las diferentes etapas del desarrollo.
Palabras clave: comparación de magnitudes, desarrollo, efecto de distancia, formato de presentación.

Correspondence concerning this article should be addressed to Danilka Castro Cañizares. Centro de Neurociencias de Cuba. Ave 25 No. 15202 esq. 158. Cubanacán, Playa. Ciudad Habana. (Cuba). E-mail: danilkac@cneuro.edu.cu

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

Current scientific literature distinguishes between basic numerical skills (subitizing, counting and number comparison), which appear to be somehow genetically controlled, and the acquisition of more complex arithmetical abilities related to the mastery of concepts and mathematical procedures depending on formal schooling (Estévez, 2005). So that, the development of the mathematical learning processes cannot be explained exclusively considering the natural trajectory of development, highly dependent on biological maturation, but it would also considered the social and cultural trajectory depending on schooling (Álvarez & Del Río, 1990; Vigotsky, 1987).

The basic numerical skills dedicated to magnitude processing that emerging early in childhood, are frequently considered the core knowledge underlying the subsequent development of numerical processing and the complex arithmetical abilities (Halberda, Mazzocco, & Feigenson, 2008; Holloway & Ansari, 2009; Kaufmann, Handl, & Thoeny, 2003). This statement is based on recent research results, suggesting there is an innate deficit in the "numerical module" (Butterworth, 1999) or "number sense" (Dehaene, 1992; Wilson & Dehaene, 2007) underlying to the specific development deficits (usually called Developmental Dyscalculia). It´s been demonstrated dyscalculic exhibit poorer achievement compared to controls in tasks engaging basic numerical processing such as non-symbolic quantities comparison and counting small sets of dots (Landerl, Bevan, & Butterworth, 2004; Landerl, Fussenegger, Moll, & Willburger, 2008).

Developmental features of numerical representations: Symbolic and Non Symbolic processing

Achievement in numerical tasks is often affected by the stimuli presentation format. Quantities can be represented through symbols: using letters (number words, roman numbers (e.g. four or IV, respectively) or Arabic code (e.g. 4), which generally involves a semantic analysis of the presented item; or through non symbolic stimuli (collection of objects). Processing of the latter is being closely related to perceptual non-numerical cues that naturally covary with numerosity (e.g., continuous quantities such as area, density, and the surface area occupied by the stimulus; see Mix, Huttenlocher, & Levine, 2002, for a review).

It is widely accepted that, depending on its different nature (perceptive vs. conceptual), the automaticity degrees of the access to magnitude representations (non-symbolic and symbolic), differ significantly through development. On the one hand, non symbolic magnitudes are processed automatically since very early ages, and it´s less depended on maturational processes and schooling, while the access to symbolic magnitude becomes automatic with the development of numerical abilities and arithmetic knowledge during formal schooling (Butterworth, 1999; Dehaene, 1997; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002).

In spite of the above, several evidences support that both types of magnitude representations (non-symbolic and symbolic) are closely related. Moyer and Landauer (1967) stated that, to perform symbolic comparisons, subjects convert numbers and numerals into analog magnitudes. Thus, although number can be represented with arbitrary symbols (e.g. '2' or 'two'), a nonverbal representation with an analog format underlies these symbols (Brannon, 2006). Similarly, it has been suggested that developing of the symbolic representational system dedicated to quantity representation, acquired during formal schooling of mathematics, can influence the non-symbolic representations previously acquired. The results reported by Pica, Lemer, Izard, and Dehaene (2004) provide experimental evidence in support of this idea. These authors assessed adults with different cultural backgrounds (indigenous adults and schooling adults) and found (by calculating the Weber fraction: a psycho-physiological parameter reflecting the amount of change in a stimulus's magnitude that is required for these stimulus to be perceived as a different one) that in non-symbolic estimation tasks, adults' results were closer to the exact values than the adults from indigenous cultures (0.12 and 0.17 respectively), who do not have a verbal code to "label" quantities.

Classical effects reported in the study of basic numerical skills development: Numerical Size and Distance Effects.

Most of the available evidences about basic numerical skills development have been obtained in studies using quantities comparison tasks. On these studies it has identified the following robust effects: numerical size effect (NSE) and numerical distance effect (NDE).

NSE expresses that, for equal numerical distance, reaction times (RTs) increase with the size of the numbers (e.g., –3 versus 7–8). This size effect has been reported in several studies (e.g., Antell & Keating, 1983; Noël, Rousselle, & Mussolin, 2005; Rousselle & Nöel, 2007; Strauss & Curtis, 1981). According to Dehaene et al. (Dehaene, 1992; Dehaene, Dupoux, & Mehler, 1990), an explanation for NSE is to assume the mental number line can be compressed, in a way that, when numerical distance remains equal, the subjective distance between corresponding mental representations decreases as the numbers' magnitudes increase.

The other feature of quantities processing, the NDE, refers to the fact that the RTs decrease monotonously as the numerical distance between the two numbers increases (e.g., 7–8 versus 7–2) (e.g., Banks, Fujii, & Kayra-Stuart, 1976; Barth et al., 2006; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Moyer & Landauer, 1967; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002).

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

The NDE appears either in Arabic numbers comparisons or in collection comparisons (Ansari, Dhital, & Siong, 2006; Barth, Kanwisher, & Spelke, 2003; Buckley & Gillman, 1974) and numerals (Ansari, Fugelsang, Dhital, & Venkatraman, 2006; Pinel, Dehaene, Riviere, & Le Bihan, 2001), indicating this effect is not constrained by the stimulus's format. In addition, NDE is not limited to the realm of numbers. Non-numerical magnitudes judgment, such as line length (Johnson, 1939) and object size (Moyer, 1973) exhibits a similar NDE. It has been suggested that magnitude comparison (numerical and non-numerical) relies on similar mechanisms (Moyer & Landauer, 1967; Walsh, 2003). Thus, NDE is thought to arise from the characteristics of a quantity's semantic representation (Dehaene, 1996; Dehaene, Dehaene-Lambertz, & Cohen, 1998).

Concurring evidences show that children exhibit the NDE since 5 years of age and the magnitude of this effect decreases in school-age (Duncan & McFarland, 1980; Holloway & Ansari, 2008; Sekuler & Mierkiewicz, 1977). In order to explain these findings, Sekuler and Mierkiewicz (1977) proposed three different types of developmental changes in numerical representation:

1) The subjective distance among numerosities in a numerical mental line could increase through development;
2) The variability of representations could decrease through development; and
3) Both changes could occur simultaneously.

This decrease in the magnitude of the NDE may reflect an increased in the accuracy of non-symbolic representations of children or an improved in the mapping between non-symbolic and symbolic representations. Although it has been frequently suggested that non-symbolic abilities in children are related to their ability to learn arithmetic (Butterworth, 1999; Dehaene, 1997), only recently this relation has began to be empirically evaluated. Booth and Siegler (2008) found that children's ability to locate symbolic representations on a mental number line is related to arithmetic achievement and the accuracy on the addition problems resolution as much as with future arithmetical acquisitions. However, it remains unclear how representations on the mental number line are linked to symbolic representations of quantity.

In accordance with these data and in order to evaluate basic numerical processing abilities, Landerl and Kölle (2009) evaluated children of second, third and fourth grades using a quantities comparison task. The results showed a distance effect in all groups and decreasing TR as age increased. In addition, Halberda, Mazzocco, and Feigenson (2008) published the results of a longitudinal study aimed to determine whether the features of approximate numerical representations could predict individual differences in achievement on mathematical tasks presented in symbolic format. These results showed the properties of approximate representations retrospectively predict the results of children in mathematic symbolic tasks.

Other evidence that describes the improvement of numeric representations through development are the ones obtained in experiments where collections of dots or sound patterns are presented. These presentations are time-controlled to prevent counting. On these tasks, unlike children, adults can discriminate numerosities even when continuous variables are controlled for. This discrimination is bound to a ratio limit, which is similar in the different format of stimuli presentation (Barth, Kanwisher, & Spelke, 2003; Cordes, Gelman, Gallistel, & Whalen, 2001; Huntley-Fenner & Cannon, 2000; Temple & Posner, 1998; Whalen, Gallistel, & Gelman, 1999). Likewise, has been demonstrated that small children with a normal intellectual quotient exhibit a larger RT and make much more errors, when comparing digits, than older children (Duncan & McFarland, 1980; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Sekuler & Mierkiewicz, 1977). Cross-sectional studies with different age groups analyzing the processing of numerical symbol (digits) through Stroop paradigms (Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002) indicate the congruency effect of size (the numeric value of Arabic symbols is activated faster than the physical properties of the stimulus, even when the latter is the relevant dimension) increases with age, and that the interference component appears earlier than the facilitation component (Landerl & Kölle, 2009).

To explain these developmental changes, Logan (1988) proposed that, two qualitatively different processes are at work during number comparison in adults: an algorithm-based process in which number magnitudes are compared at the semantic level, and a faster memory-based process which consists of directly retrieving the correct answer from memory. Initially, children would only be able to compare digits using the algorithmic process. But, with age, their growing experience with Arabic digit comparison would lead them to develop long-term memory associations between the digit pair to be compared and the correct response. As a consequence, access to the representation of numerical magnitude becomes automatic. Accordingly, it has been argued that numerical distance and size effects designate an automatic activation of the mental number line.

The potential importance of the mapping between symbolic and non-symbolic representations to learning mathematics has been supported in studies with dyscalculic children. Rousselle and Noël (2007) probed that children with arithmetic learning disabilities were slower and more error prone than controls in a symbolic comparison task. However, they did not exhibit deficit in non-symbolic comparisons. The authors concluded that children with arithmetic learning disabilities have no difficulty in processing numerosity per se but rather in accessing numerical meaning from symbols. Suggesting the connection between both representational systems is crucial to learning symbolic mathematics in school.

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

As has been described above, up to now, the results of currents researches point to, the processing of quantities becoming automatic as age and schooling increases, however, most of the studies have evaluated the development of basic numerical skills using stimuli only one presentation format (Girelli, Lucangeli, & Butterworth, 2000; Halberda & Feigenson, 2008; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). In contrast, others have employed both formats, but in studies with only one age group, so they could not account the development of numerical processing features (Izard & Dehaene 2008; Lipton & Spelke, 2005). Taking to account the view that basic numerical skills underlying later development of numerical processing, and the critical importance of the mapping between both representational systems (non-symbolic and symbolic) to learning formal symbolic mathematics, the aim of this study is to describe the typical development of symbolic and non-symbolic quantity processing in school-aged children. In other words, this study aims not only to support the quantitative change that occurs in numerical processing ability with age (which has been characterized in several research), but to detailed on what differences specifically make this processing qualitatively different across the age groups studied.

Method

Participants

Ninety-one Cuban, school-aged children were selected (forty-four female and forty-seven male): thirty-one first-graders, thirty-one third-graders and twenty-nine sixth-graders (see age details in Table 1). To be included in the sample, the children could show no sign of learning or behaviour disorders according to the Signs of at-Risk Learning Disabilities Questionnaire (on items concerning arithmetic learning) and the Signs of at-Risk Behavior Disorders Questionnaire (Pérez, 2009). Also, they had to score between the 50th and 95th percentile for age on the Ravens Colored Progressive Matrices Test (Raven, J.C., Court, & Raven, J., 1992), according to the Chilean norms (Ivanovic, R. et al., 2000) (see Table 1).

Following the above requirements, to selected children, the Digit Span Scale (forward and backward) of the Weschler Intelligence Scale for Children (Revised) (WISC-R) (Sattler, 1982), was administered; because many evidences support that that working memory plays a central role in mathematical achievement (Geary, 1993; 1994; Geary, Brown, & Samaranayake, 1991; Koontz & Berch, 1996; McLean & Hitch, 1999; Passolunghi & Siegel, 2004). The results of this test are displayed in Table 1.

Materials and Procedure

Experimental Tasks

The experimental tasks were run using the stimulus presentation software SuperLab 4.0 for Windows XP/2000. As all experimental tasks required choosing between two possible responses, one displayed on the left and one displayed on the right side of the screen, children were always asked to respond by pressing the button on the side of the correct response. The computer automatically recorded the reaction time of each response. Instructions emphasized both speed and accuracy. Each task was preceded by 8 training trials.

Simple Reaction Time Task: Some children are relatively slow at pressing keys in response to any stimuli. The simple reaction time test was designed to evaluate this. The score on this test was not analyzed by itself. Instead, the reaction times on the remainder experimental tasks described below were adjusted taking this measure into account (see statistical analysis section).

Children were presented a white background with a blue circle, which appears counterbalanced across the left or the right side of the screen. Children were asked to press the key corresponding to the side where the circle appears. Each trial started with the presentation of a blue circle until response, followed by inter-stimulus interval that varying between 100 and 1500 ms (white screen).

Table 1
Subject details

	N total = 91					
	1st grade (*n* = 31)		3rd grade (*n* = 31)		6th grade (*n* = 29)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age (years)	6.41	.32	8.56	.29	11.30	.36
Raven Score (Percentile)	23.90 (92.92)	3.31	27.73 (83.5)	4.59	31.45 (87.31)	2.63
Forward Digit Span Score	4.93	1.57	5.74	1.67	7.03	1.95
Backward Digit Span Score	3.00	.77	4.74	1.21	5.69	1.58

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

Symbolic Task

Arabic number comparison: Two Arabic digits from 1 to 9 (Arial, 48-point font) were presented on the computer screen (white background) and children were asked to select the larger of the two digits. Comparison pairs varied along two numerical size and two distance between digits: small pairs (digits from 1 to 5) were contrasted with large pairs (digits from 5 to 9) and close pairs (distance of 1) were compared with far pairs (distance of 3 or 4). Three different pairs of digits were used in each experimental sub-condition (see Table 2). Digit pairs appeared in a fixed pseudo-random order (the same item never appeared in two consecutive trials). The side of the correct response was counterbalanced: each pair appeared four times, twice in ascending (e.g., 1–2) and twice in descending (e.g., 2–1) order, for a total of 48 pairs of single-digit number to be compared (3 digit pairs X 2 sizes X 2 distances X 2 sides X 2 presentations). Each trial started with the presentation of a digit pair until response, followed by an ISI (white screen) of 500 ms.

Table 2
Single-Digit pairings used on Arabic numbers comparison task

	Distance	
Size	Close	Far
Small	1–2	1–4
	2–3	1–5
	3–4	2–5
Large	6–7	5–8
	7–8	5–9
	8–9	6–9

Non-symbolic Task

Collection comparison: Children were simultaneously presented with two white squares (side = 55 mm) containing a variable number of vertical black rectangles or small blue squares, and were instructed to select the one that contained more elements. Both white squares were presented on a dark grey background and were separated by a fixation cross (distance between squares = 8 mm). The task was administered in three conditions of perceptual control: density, surface and area.

In the condition controlling for density, all sticks were of equal size (2 mm wide and 6 mm high). In the condition controlling for surface, the total surface area of the sticks was equated in each pair by reducing the size of the elements in the collection with more sticks. To avoid the larger collection in number being also the one with the smaller elements, sticks of different height were used and the size of the smaller and larger sticks was the same in both arrays to be compared. Furthermore, the external perimeter of both collections was identical within each pair (drawn from Rousselle, Palmers, & Noël, 2004) (see Table 3).

In both, density and surface conditions, comparison arrays involved the same numerosities as those used for large pairs in Arabic number comparison task (see Table 2). Consequently, these comparison pairs varied along two distances (close and far). The pairs of collection appeared twice in ascending (e.g., 5-8) and twice in descending (e.g., 8-5) order, for a total of 24 pairs of numerosities to be compared (3 pairs of numerosities X 2 distances X 2 sides X 2 presentations)

In the condition controlling for area, the total area occupied for small blue squares inside white squares (side = 2,13 cm) and the distance between these (it was never smaller than eight pixels) were controlled. The sum of the small blue squares total area was the same in the two arrays (total area = .56 cm2), by reducing the size of the elements in the collection with more squares (see Table 3). On this task, the same pairs presented in Arabic comparison tasks were used. The side of the correct response was counterbalanced: each pair appeared four times, twice in ascending (e.g., 1–2) and twice in descending (e.g., 2–1) order, for a total of 48 pairs of collections to be compared (3 numerosity pairs X 2 sizes X 2 distances X 2 sides X 2 presentations).

In the three perceptual conditions, comparison pairs were presented in a fixed pseudo-random order. Each trial started with the presentation of a collection pair until response, followed by an ISI of 500 ms during which the fixation cross remained in full view.

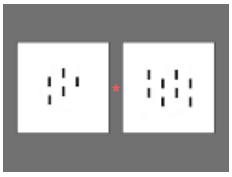
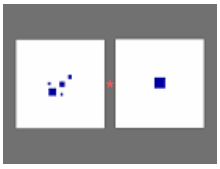
Children were tested individually in a quiet room at the school, with adequate conditions of lighting, ventilation, etc. A single testing session of 30–40 minutes was necessary for each child. The session started with the Simple Reaction Time Task. After that, the remaining tasks were administered in a counterbalanced order.

Statistical Analysis

Analyses were performed using the median RTs of correct responses only. These medians correspond to a quantity of correct responses equal or greater than 50% for each experimental sub-condition, thereby excluding of analyses the results of children who responded al the chance level (number of correct responses equal or less than 50%). Medians of RTs for correct responses by condition for both, Arabic and collection tasks were adjusted subtracting each by the median of the simple RT of each child (adjRTs) in order to control the variability of RT due to individual differences.

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

Table 3
Controlled perceptual features for collection comparison tasks

Perceptual Condition	Perceptual Variables					
	Density[a]	External contour length[b]	Total Área Occupied on the Screen	Total Surface [c]	Total Perimeter[d]	Size of the elements
Density 	*					*
Area 			*	*		
Surface 		*	*	*	*	

The asterisk (*) indicates that the perceptual variable is controlled.
[a] The proportion of occupied positions on the screen divided by the total number of available positions.
[b] Perimeter delineated by external elements of collection.
[c] Sum of the area of all elements of collection.
[d] Sum of perimeter of all elements of collection.

To analyze results of collection comparison tasks, the data of the three perceptual conditions (density, surface and area) were collapsed, considering that evidences from previous studies support that, although for non-symbolic comparisons the subjects based on perceptual non-numerical cues, their results are generally similar (in both, RT and accuracy) regardless of the perceptual control used (Luculano, Tang, Hall, & Butterworth, 2008; Rousselle & Nöel, 2007; Rousselle, Palmers, & Noël, 2004).

Next, differences in Raven and working memory scores among groups were tested using T tests for independent samples. If significant differences were found, then, these scores were used as covariates in the remainder analyses. The experimental data was analyzed using two ANCOVAs to assess the classical effects of numerical processing: the numerical size and distance effects. ANCOVA is a parametric statistic which assumes normal data distribution and variance homogeneity when two or more samples are being compared. Shapiro–Wilk's normality test and Levene's variance homogeneity test indicated that the RTs and accuracy data did not completely fit these parametric assumptions. Therefore, a logarithmic transformation of adjRTs was performed.

To analyze numerical size effect, the responses of each task (symbolic and non-symbolic) were collapsed into two variables: small size and large size. Median of adjRTs was calculated for both. A similar procedure was used to analyze the numerical distance effect, but the responses were collapsed into following variables: close distance and far distance.

Results

Finally, in each analysis data from sixty-eight children were included: Twelve first-graders, twenty-six third-graders and twenty-five sixth-graders.3.1 Analysis of Numerical Processing Effects.

Analysis of Numerical Size Effect

Data were analyzed using an ANCOVA with numerical size (small, large) and presentation format (symbolic, non-

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

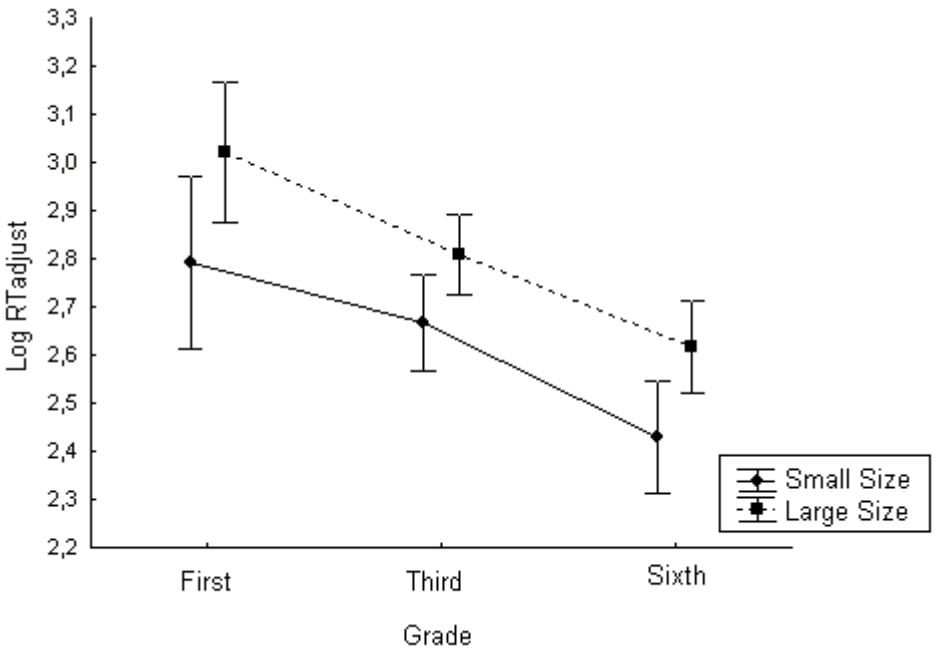


Figure 1. Numerical Size Effect by Grade.

symbolic) as within-subject factors, and grade (1, 3, 6) as between-subjects factor. Raven and Digit Span (forward and backwards) scores were included as covariates.

This analysis show significant effect of grade: $F(2,61) = 12{,}375$, $p < .001$. At processing stimuli, sixth grade children (M = 579.21 ms; SD = 45.55 ms) were significantly faster than third grade children (M = 849.31 ms; SD = 37.47 ms; $p < .001$), and third grade children were significantly faster than those in first (M = 1,254.38 ms; SD = 67.84 ms; $p < .001$). Numerical size effect was no found, but pairs of small sizes were processed faster (M = 762.51 ms; SD = 21.96 ms) than those of large sizes (M = 1,022.21 ms; SD = 32.7 ms). There was no effect of format found either, but the symbolic pairs were processed faster (M = 655.16 ms; SD = 43.33 ms) than non-symbolic ones (M = 1,133.44 ms; SD = 46.55 ms).

Numerical size by grade interaction was found: $F(2, 61) = 3.6214$, $p < .05$. Planned comparisons showed the following differences among groups: First-graders were significantly slower at processing large sizes than third-graders ($p < .001$; first grade: M = 2,898.98 ms; SD = 520.74 ms; third grade: M = 1,430.21 ms; SD = 413.59 ms) and sixth-graders ($p < .001$; sixth grade: M = 1,132.18 ms; SD = 351.56 ms). In addition, sixth-graders were significantly slower at processing small sizes ($p < .001$; first grade: M = 1,563.27 ms; SD = 363.61 ms; sixth grade: M = 849.06 ms; SD = 245.56 ms). Additionally, third-graders were significantly slower than sixth-graders at processing both small ($p < .001$; third grade: M = 1,088.87 ms; SD = 266.87 ms) and large sizes ($p < .001$) (see Figure 1).

Also, presentation format by grade interaction was found: $F(2,61) = 8.1889$, $p < .001$. Planned comparisons showed the following data: First-graders process non-symbolic stimuli significantly faster than symbolic stimuli ($p < .01$; non-symbolic format: M = 1,773.87 ms; SD = 464.68 ms; symbolic format: M = 1,895.83 ms; SD = 535.46 ms). Conversely, third-graders process symbolic stimuli faster than non-symbolic stimuli, although these differences are no significant (symbolic format: M = 1,144 ms; SD = 330.89 ms; non-symbolic format: M = 1,304.05 ms; SD = 359.52 ms). Finally, sixth-graders process symbolic stimuli significantly faster than non-symbolic stimuli ($p < .01$; symbolic format: M = 883.35 ms; SD = 315.86 ms; non-symbolic format: M = 1,041.03 ms; SD = 288.91 ms) (see Figure 2). No presentation format by numerical size interaction was found, nor presentation format by numerical size by grade interactions.

Analysis of Numerical Distance Effect

Data were analyzed using an ANCOVA with numerical distance (close, far) and presentation format (symbolic, non-symbolic) as within-subject factors, and grade (1, 3, 6) as between-subjects factor. Raven and Digit Span (forward and backwards) scores were included as covariates.

This analysis show significant effect of grade: $F(2, 62) = 19{,}290$, $p < .001$. At processing stimuli, sixth grade children were significantly faster than third grade children ($p < .0001$; sixth grade: M = 825.60 ms; SD = 55.15 ms;

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

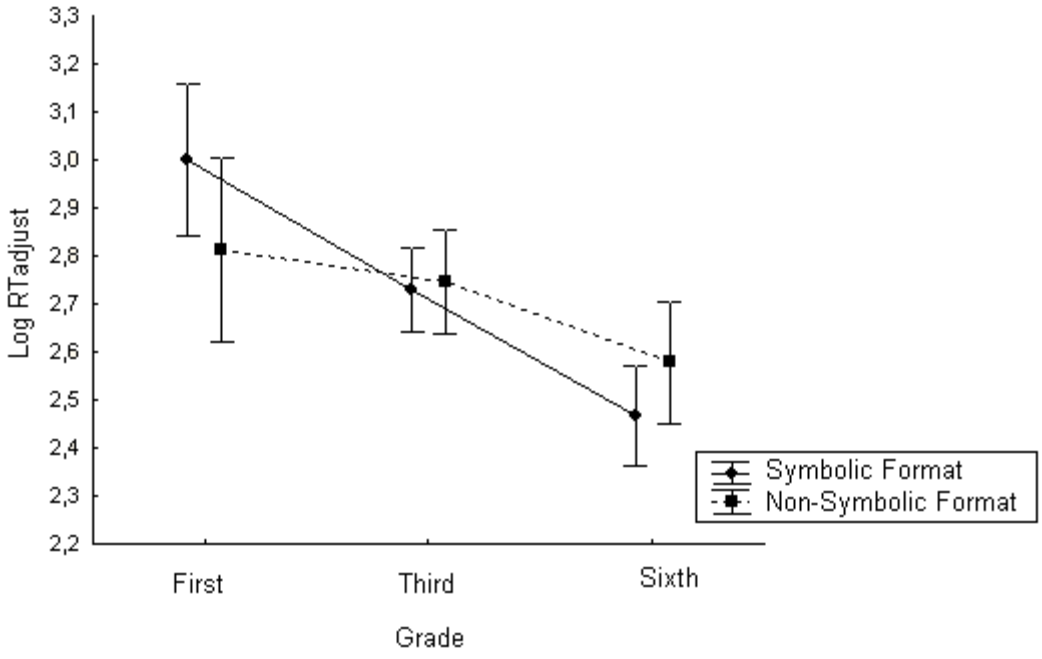


Figure 2. Numerical processing by grade for both stimulus presentation formats (symbolic vs. non-symbolic).

third grade: M = 1,160.36 ms; SD = 45.37 ms). Also, third-graders were faster than first-graders ($p < .001$; first grade: M = 1,654.10 ms; SD = 82.13 ms). Furthermore, there was a main effect of distance: $F(1,62) = 16.337$, $p < .001$. Pairs with far distances were compared significantly faster (M = 1084.14 ms; DE = 39.46 ms) than pairs with close distances (M = 1342.57 ms; DE = 55.72 ms). Presentation format was not found, although symbolic pairs (M = 1,198.76 ms; SD = 48.11 ms) were compared faster than non-symbolic pairs (M = 1,227.95 ms; SD = 55.91 ms).

Presentation format by numerical distance interaction was found: $F(1,62) = 7,7800$, $p < .01$. When the most difficult numerical distances were compared (close distances), significant differences in RTs between presentation formats were found: Symbolic format was processed more quickly than non-symbolic format ($p < .01$; symbolic format: M = 1,267.39 ms; SD = 571.93 ms; non-symbolic format: M = 1,653.50 ms; SD = 628.42 ms). However, when numerical distances between comparison pairs were far, the achievement was similar for both presentation formats (symbolic format: M = 1,175.04 ms; SD = 510.23 ms; non-symbolic format: M = 1,142.27 ms; SD = 376.02 ms).

Also, numerical distance by grade interaction was found: $F(2,62) = 3.9678$, $p < .05$. Planned comparisons showed the following significant differences among groups: First-graders process both, close and far distances, significantly slower than third-graders (close distances: $p < .01$; first grade: M = 2,200.44 ms; SD = 496.64 ms; third grade: M = 1,521.91 ms; SD = 454.72 ms; far distances: $p < .01$; first grade: M = 1,633.23 ms; SD = 399.93 ms; third grade: M = 1,119.08 ms; SD = 277.79 ms). Similar achievement was showed to compare results between first and sixth graders (close distances: $p < .001$; sixth graders: M = 1,186.22 ms; SD = 409.9 ms; far distances: $p < .001$; sixth graders: M = 891.49 ms; SD = 234.34 ms) and the results between third and sixth-graders (close distances: $p < .001$; far distances: $p < .001$) (see Figure 3).

Presentation format by grade interaction was no found, although planned comparisons showed the following data: First-graders process non-symbolic stimuli faster than symbolic stimuli, but these differences was not found to be statistically significant (non-symbolic format: M = 1,892.14 ms; SD = 533.38 ms; symbolic format: M = 1,924.15 ms; SD = 499.79 ms). Conversely, third-graders process symbolic stimuli significantly faster than non-symbolic stimuli ($p < .05$; symbolic format: M = 1,144.38 ms; SD = 329.49 ms; non-symbolic format: M = 1,409.02 ms; SD = 414.03 ms). The same achievement was showed for sixth-graders ($p < .05$; symbolic format: M = 876.5 ms; SD = 313.95 ms; non-symbolic format: M = 1,130.61 ms; SD = 341.45 ms). Neither interaction format by distance by grade was found.

Discussion

The data collected reveal that, in all groups of children, classical effects of numerical processing (distance and size) appears when stimuli display in different formats are processed. Nevertheless, significant RT decreasing in

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

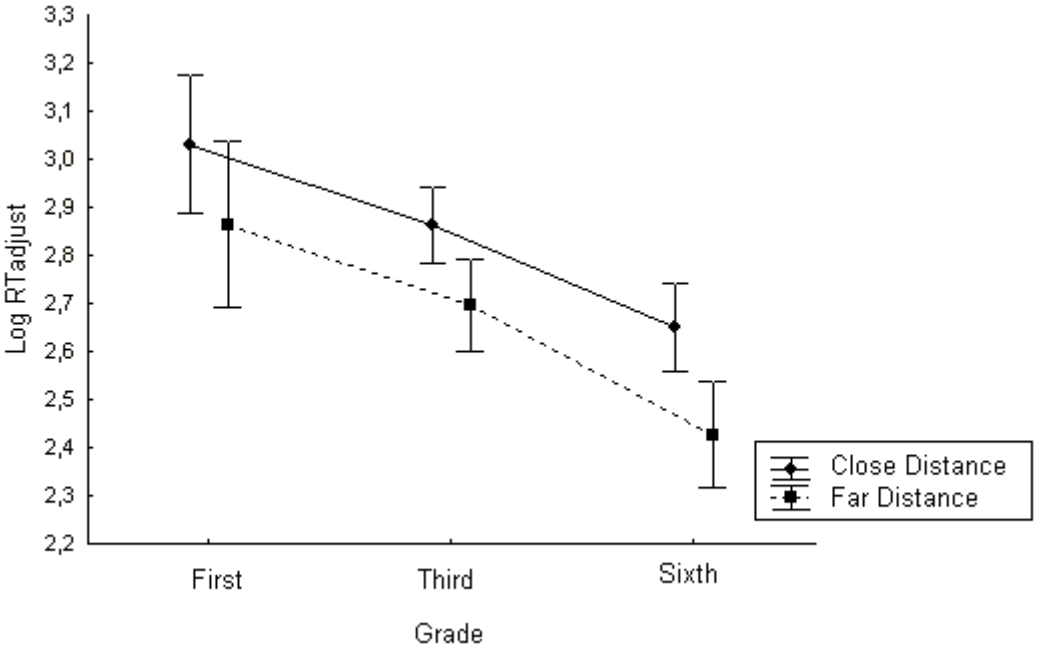


Figure 3. Numerical Distance Effect by Grade.

quantity comparisons appear when age increase, suggesting that this process becomes progressively automatic.

These results have support the findings of other cross-sectional studies with samples of different grades (Girelli, Lucangeli, & Butterworth, 2000; Landerl & Kölle, 2009; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Sekuler & Mierkiewicz, 1977) that have found significant differences between groups in numerical processing speed, and one longitudinal study (Halberda, Mazzocco, & Feigenson, 2008), in which found that the Weber fraction decreases as age increases (0.56: 5 years old, to 0.12: 14 years old).

In addition, there is experimental evidence to support the influence of education on the features of numerical representations. It has been demonstrated that children who have already acquired counting abilities has better performed on estimation tasks (Lipton & Spelke, 2005). Also, it has been reported that subjects' level of education influences the precision degree of their numerical representations (Pica, Lemer, Izard, & Dehaene; 2004). Likely, these data suggest that the decrease observed in RT as children's age increases, indicates any increase in precision of the numerical representations that are generated as one performs a comparison task. To confirm this, however, we would need to apply the appropriate mathematical methods to calculate the Weber fraction of each child.

After performing a comparative analysis of each group of children' performance on symbolic and non-symbolic tasks, the data suggests a qualitative transformation through the development course in the pattern of ability to process both formats. In accordance with the findings of earlier studies (Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002), the first-graders processed quantities presented in non-symbolic format significantly faster than items presented in symbolic format. On the other hand, third and sixth-graders begin to process symbolic quantities significantly faster. These patterns of performance support previous affirmations that access to numerical symbols improve through development of formal learning (Rubinsten, Henik, Berger, & Shahar-Shalev, 2002) and that mathematical understanding increases considerably over the course of education (Rico, Santos, & Martin-Viana, 2004). In this way, a child begins to substitute operations with objects for operations with abstract numerical systems. According to Vigotsky (1987), children in this stage of development come to understand the limitations of their natural arithmetic skills and start to move on to arithmetic mediated by numerical symbols.

Bearing in mind that, the decrease in RT found in this study could be explained by the fact that older children have more understanding and more experience with numerical symbols. While learning mathematical abilities, they develop long-term memory associations between digit pairs being compared and their corresponding correct responses. This leads them to automatize the process of quantity comparison, resulting in decreased RT of the task (Logan, 1988; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Tzelgov, Meyer, & Henik, 1992). On the other hand, the quantitative differences found among groups could be

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

associated with qualitative changes produced gradually in mental representations of quantity. For example, it is possible that the spatial orientation of the mental number line, and the mapping between labels or symbols associated with quantity and its corresponding numerical magnitudes are developed around third grade, so sixth-graders would be at an advantage when it comes to processing Arabic numbers. Along the lines of the ideas described above, when comparing close distances, subjects compared quantities in symbolic format faster than non-symbolic comparisons, which also suggests that mastery of the associated symbols may facilitate numerical processing. Nevertheless, empirical evidence would be needed to support this hypothesis.

In addition, results on non-symbolic task of magnitude comparison showed a similar increase in processing speed with age. This suggests that the mental mechanism underlying performance on the task in symbolic format is increasingly independent of perceptual variables. That is to say, it improves the efficiency with which quantity is detected despite the strict control of the perceptual variables employed.

Conclusions

The present research, assessed numerical processing using a developmental approach, contrasting with the most studies in which, the understanding of developmental disorders it's based on neuropsychological models that reflect the adult (stable and completely developed) cognitive system features. Also, this study allowed assessing within the same sample, the development of numerical processing as much symbolic presentation format task as non-symbolic presentation format task.

In a general way, we stated that when age and education increase, to appear a significant automaticity in basic numeric process of magnitudes comparison. Although no interactions among groups by the classical numerical processing effects (distance/ size) by the quantities' presentation format were found, the data show that through the course of development, quantitative and qualitative differences occur in quantity processing, both symbolic and non-symbolic.

Our results suggest that the presentation of Arabic numbers do not always automatically activate the internal representations of the magnitudes that link to these numbers, but connection process of non-symbolic and semantic (analogical) quantity representations occurs through a specific evolving process, based on the early cognitive system specialization for numerical size representation of object collections. Like that, autonomous processing of numerical information emerges gradually as subjects develop numerical abilities and progressively acquire arithmetic understanding.

Finally, these results support hypothesis that Developmental Dyscalculia may result from a deficit in access to the numerical magnitude from symbols (Rousselle & Nöel, 2007; Wilson & Dehaene, 2007). The present findings open many new perspectives to improve the development of numerical abilities and to research on mathematical learning disabilities. Topics such as the dissociation between symbolic and non-symbolic quantities processing in learning disabilities children, and intensive training to learn links between approximate quantities and Arabic numbers (Hasher & Zacks, 1979; Logan, 1988) could be relevant to design tasks and methods to enhance development, and to diagnosis and intervention on mathematical learning disability.

References

Álvarez, A., & del Río, P. (1990). Educación y desarrollo: la teoría de Vigostky y la zona de desarrollo próximo [Education and Development: Vigostky´s theory and the zone of proximal development]. In C. Coll, J. Palacios, & A. Marchesi (comps.), *Desarrollo Psicológico y educación* [Psychological development and education II] (Vol II, pp. 93-119). Madrid: Alianza.

Ansari, D., Dhital, B., & Siong, S. Ch. (2006). Parametric effects of numerical distance on the intraparietal sulcus during passive viewing of rapid numerosity changes. *Brain Research*, *1067*, 181-188. doi:10.1016/j.brainres.2005.10.083

Ansari, D., Fugelsang, J., Dhital, B., & Venkatraman, V. (2006).Dissociating response conflict from numerical magnitude processing in the brain: an event-related fMRI study. *NeuroImage*, *32*(2), 799-805. doi:10.1016/j.neuroimage.2006.04.184

Antell, S. E., & Keating, D P. (1983). Perception numerical invariance in neonates. *Child Development*, *54*, 695-701. doi:10.1111/j.1467-8624.1983.tb00495.x

Banks, W. P., Fujii, M., & Kayra-Stuart, F. (1976). Semantic congruity effects in comparative judgments of magnitudes of digits. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 435-447. doi:10.1037/0096-1523.2.3.435

Barth, H., Kanwisher, N., & Spelke, E. (2003). The construction of large number representations in adults. *Cognition*, *86*, 201-221. doi:10.1016/S0010-0277(02)00178-6

Barth, H., La Mont, K., Lipton, J., Dehaene, S., Kanwisher, N., & Spelke, E. S. (2006). Non symbolic arithmetic in adults and young children. *Cognition*, *98*, 199-222. doi:10.1016/j.cognition.2004.09.011

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development, 79*, 1016-1031. doi:10.1111/j.1467-8624.2008.01173.x

Brannon, E. M. (2006). The representation of numerical magnitude. *Current Opinion in Neurobiology*, *16*, 222-229. doi:10.1016/j.conb.2006.03.002

Buckley, P. B., & Gilman, C. B. (1974). Comparison of digits and dot patterns. *Journal of Experimental Psychology, 103,* 1131-1136. doi:10.1037/h0037361

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

Butterworth, B. (1999). *The mathematical brain*. London: Macmillan.

Cordes, S., Gelman, R., Gallistel, C. R., & Whalen, J. (2001). Variability signatures distinguish verbal from nonverbal counting for both large and small numbers. *Psychological Bulletin*, *8*(4), 698-707. doi:10.3758/BF03196206

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1-42. doi:10.1016/0010-0277(92)90049-N

Dehaene, S. (1996). The organization of brain activations in number comparison: Event-related potentials and the additive-factors methods. *Journal of Cognitive Neuroscience*, *8*, 47-68. doi:10.1162/jocn.1996.8.1.47

Dehaene, S. (1997). *The number sense*. New York, NY: Oxford University Press.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neurosciences, 21*, 355-361. doi:10.1016/S0166-2236(98)01263-6

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. J*ournal of Experimental Psychology: Human Perception and Performance, 16*, 626-641. doi:10.1037//0096-1523.16.3.626

Duncan, E. M., & McFarland, C. E. (1980). Isolating the effects of symbolic distance and semantic congruity in comparative judgments: An additive-factors analysis. *Memory & Cognition*, *8*, 612-622. doi:10.3758/BF03213781

Estévez, N. (2005). *Developmental Dyscalculia. A neuropsychological and morphometric study* . (Unpublished master's thesis). Universidad de la Habana, La Habana, Cuba.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin, 114*, 345-362. doi:10.1037//0033-2909.114.2.345

Geary, D. C. (1994). *Children's mathematical development: Research and practical applications.* Washington, DC: American Psychological Association.

Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive addition: A short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. *Developmental Psychology*, *27*, 787-797. doi:10.1037//0012-1649.27.5.787

Girelli, L., Lucangeli, D., & Butterworth, B. (2000). The development of automaticity in accessing number magnitude. *Journal of Experimental Child Psychology*, *76*, 104-122. doi:10.1006/jecp.2000.2564

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. doi:10.1037/a0012682

Halberda, J., Mazzocco M. M., & Feigenson, L. (2008). Individual differences in nonverbal number acuity correlate with maths achievement. *Nature, 455*, 665-668. doi:10.1038/nature07246

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General, 108*, 356-388. doi:10.1037//0096-3445.108.3.356

Holloway, I., & Ansari, D. (2008). Domain-specific and domain-general changes in children's development of number comparison. *Developmental Science*, *11*, 644-649. doi:10.1111/j.1467-7687.2008.00712.x

Holloway, I., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology*, *103*, 17-29. doi:10.1016/j.jecp.2008.04.001

Huntley-Fenner, G., & Cannon, E. (2000). Preschoolers' magnitude comparisons are mediated by a preverbal analog mechanism. *Psychological Science*, *11*, 147-152. doi:10.1111/1467-9280.00230

Ivanovic, R., Forno, H., Durán, M. C., Hazbún, J., Castro, C., & Ivanovic, D. (2000). Estudio de la capacidad intelectual (test de matrices progresivas de Raven) en escolares chilenos de 5 a 18 años. Antecedentes generales, normas y Recomendaciones [Intellectual capacity study (Raven's Coloured Progressive Matrices) in chilean children from 5 to 18 years of age. General background, standards and recommendations]. *IberPsicologia*, *53*(1), 5-30.

Izard, V., & Dehaene, S. (2008). Calibrating the mental number line. *Cognition, 106*(3), 1221-1247. doi:10.1016/j.cognition.2007.06.004

Johnson, D. M. (1939). Confidence and speed in the two-category judgment. *Archives of Psychology*, *34*, 1-53.

Kaufmann, L., Handl, P., & Thoeny, B. (2003). Evaluation of a numeracy intervention program focusing on basic numerical knowledge and conceptual knowledge. A pilot study. *Journal of Learning Disabilities*, *36*, 564-573. doi:10.1177/00222194030360060701

Koontz, K. L., & Berch, D. B. (1996). Identifying simple numerical stimuli: processing inefficiencies exhibited by arithmetic learning disabled children. *Mathematical Cognition*, *2*(1), 1-23. doi:10.1080/135467996387525

Lander, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: a study of 8–9-year-old students. *Cognition, 93*, 99-125. doi:10.1016/j.cognition.2003.11.004

Landerl, K., Fussenegger, B., Moll, K., & Willburger, E. (2008). *Dyslexia and dyscalculia: Two learning disorders with different cognitive profiles*. Unpublished manuscript, University of Tübingen, Tübingen, Germany.

Landerl, K., & Kölle, C. (2009). Typical and atypical development of basic numerical skills in elementary school. *Journal of Experimental Child Psychology*, *103*(4), 546-565. doi:10.1016/j.jecp.2008.12.006

Lipton, J. S., & Spelke, E. S. (2005). Preschool children's mapping of number words to nonsymbolic numerosities. *Child Development*, *76*, 978-988. doi:10.1111/j.1467-8624.2005.00891.x

Logan, G. D. (1988). Towards an instance theory of automatization. *Psychological Review*, *95*, 492-527. doi:10.1037/0033-295X.95.4.492

Luculano, T., Tang, J., Hall, Ch., & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press

and low numeracy. *Developmental Science, 11*(5), 669-680. doi:10.1111/j.1467-7687.2008.00716.x

McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetical difficulties. *Journal of Experimental Child Psychology*, *74*, 240-260. doi:10.1006/jecp.1999.2516

Mix. K. S., Huttenlocher, J., & Levine, S. C. (2002). Multiple cues for quantification in infancy: Is number one of them?. *Psychological Bulletin*, *128*, 278-294. doi:10.1037//0033-2909.128.2.278

Mover, R. S. (1973). Comparing objects in memory: Evidence suggesting an internal psychophysics. *Perception & Psychophysics, 13*, 180-184.

Moyer, R .S., & Landauer, T. K. (1967). Time required for judgments of numerical inequality. *Nature*, *215*, 1519-1520. doi:10.1038/2151519a0

Noël, M.-P., Rousselle, L., & Mussolin, C. (2005). Magnitude representation in children: Its development and dysfunction. In J. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 179-195). New York, NY: Psychology Press.

Passolunghi, M. Ch., & Siegel L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Journal of Experimental Child Psychology*, *88*, 348-367. doi:10.1016/j.jecp.2004.04.002

Pérez, O. (2009). *Basic numerical processing in Cuban schoolers: Quantity comparison development.* (Unpublished B.Sc. thesis). Universidad de la Habana, La Habana, Cuba.

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science*, *306*, 499-503. doi:10.1126/science.1102085

Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage*, *14*(5), 1013-1026. doi:10.1006/nimg.2001.0913

Pinel, P., Piazza, M., LeBihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number size and luminance during comparative judgments. *Neuron*, *41*(6), 983-993. doi:10.1016/S0896-6273(04)00107-2

Raven J. C., Court, J. H., & Raven, J. (1992). *Standard progressive matrices*. Oxford, UK: Oxford Psychologists Press.

Rico, P., Santos, E. M., & Martin-Viana, V. (2004). *Proceso de enseñanza– aprendizaje desarrollador en la escuela primaria. Teoría y práctica* [Potentiation of learning processes through formal instruction in primary school. Theory and Practice]. La Habana: Pueblo y educación.

Rousselle, L., & Noël, M. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs. non-symbolic number magnitude processing. *Cognition*, *102*(3), 361-395. doi:10.1016/j.cognition.2006.01.005

Rousselle, L., Palmers, E., & Noël, M. (2004). Magnitude comparison in preschoolers: What counts? Influence of perceptual variables. *Journal of Experimental Child Psychology*, *87*, 57-84. doi:10.1016/j.jecp.2003.10.005

Rubinsten, O., Henik, A., Berger, A., & Shahar-Shalev, S. (2002). The development of internal representations of magnitude and their association with arabic numerals. *Journal of Experimental Child Psychology*, *81*(1), 74-92. doi:10.1006/jecp.2001.2645

Sattler J. M. (1982). *Assessment of children's intelligence and special abilities.* Boston, MA: Allyn & Bacon.

Sekuler, R., & Mierkiewicz, D. (1977). Children's judgments of numerical equality. *Child Development*, *48*, 630-633. doi:10.2307/1128664

Strauss, M. S., & Curtis, L. E. (1981). Infant perception of numerosity. *Child Development, 52*, 1146-1152. doi:10.1111/j.1467-8624.1981.tb03160.x

Temple, E., & Posner, M. I. (1998). Brain mechanisms of quantity are similar in 5-year-olds and adults. *Proceedings of the National Academy of Sciences of the USA*, *95*, 7836-7841. doi:10.1073/pnas.95.13.7836

Tzelgov, J., Meyer, J., & Henik, A. (1992). Automatic and intentional processing of numerical information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 166-179. doi:10.1037//0278-7393.18.1.166

Vigotsky S. L. (1987). *Historia del Desarrollo de las Funciones Psíquicas Superiores* [History of the Higher Psychological Functions Development]. La Habana: Científico Técnica.

Walsh V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*(11), 483-488. doi:10.1016/j.tics.2003.09.002

Whalen, J., Gallistel, C. R., & Gelman, R. (1999). Nonverbal counting in humans: the psychophysics of number representation. *Psychological Science*, *10*, 130-137. doi:10.1111/1467-9280.00120

Wilson, A., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In D. Coch, G. Dawson, & K. Fischer (Eds.). *Human behavior, learning and the developing brain: Atypical development*. New York, NY: Guilford Press.

Received August 13, 2009
Revision received April 15, 2010
Accepted April 27, 2010

https://doi.org/10.5209/rev_SJOP.2011.v14.n1.4 Published online by Cambridge University Press