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What Impairs Subitizing in Cerebral Palsied Children?

ABSTRACT: *The goal of this study was to investigate the factors responsible for the low subitizing limit of cerebral palsied (CP) children. For this purpose, 44 CPs were tested on two tasks involving the rapid recognition of dot configurations. The answer was either a number (subitizing task) or the name of a pattern (pattern recognition task). The CPs were compared to controls of the same age. All children were evaluated for visual and visuospatial short-term memory. The results showed that CPs with a low subitizing limit did not do better with a canonical arrangement than the random one, were impaired to the same extent on the pattern recognition task as on the subitizing task, and had a short visuospatial short-term memory span. These results suggest that the low subitizing limit of CPs stems from a (non-number-dependent) lesser capacity to perceive a dot configuration as a gestalt. A low subitizing limit was almost always associated with a right-hemisphere lesion.*
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When we evaluate the numerical quantity of discrete objects, we use one of three processes depending on the size of the display and the available amount of time: counting, estimation, and subitizing. Counting allows for the precise identification of the numerosity of collections of discrete objects, whatever their size, provided enough time is available. Estimation, which allows for the approximate identification of the numerosity of large collections, is used when there is not enough time to count or when the collection is too large for subitizing. Finally, subitizing refers to the ability to rapidly judge the numerosity of small arrays of simultaneously presented items. Several studies have shown that cerebral palsied (CP) children have trouble counting (Arp & Fagard, 2001; Camos, Fayol, Lacert, Bardi, & Laquiere, 1998; Mazeau, 1995); in addition, CP children cannot use subitizing to the same extent as control children (Arp, 2004; Arp & Fagard, 2001). CP children's counting difficulties are hypothesized to be caused by visuospatial dyspraxia, which prevents them from accurately pointing to each element of the display. Since subitizing does not involve manual pointing and is probably too fast to permit visual pointing, the lower subitizing limit of CP children is harder to explain. The goal of the study presented here was to investigate the factors likely responsible for the low subitizing limit of CP children.

Subitizing has been distinguished from the other enumeration processes by analyzing reaction time (RT) and response accuracy (Jensen, Reese, & Reese, 1950; Kaufman, Lord, Reese, & Volkmann, 1949; Saltzman & Garner, 1948; Taves, 1941). Klahr (1973) showed that when subjects are asked to report the number of elements in a display, the RT curve, although increasing with each additional element, is discontinuous: Up to five elements, the increase per added element is about 40 ms while at six elements RT rises abruptly to 300 ms per added element. The same discontinuity has been observed on accuracy (Kaufman et al., 1949; Taves, 1941). Subitizing can occur after a very short exposure (a few ms) and needs longer exposure when a mask is presented right after the items (50–100 ms for an adult; Averbach, 1963; Lorinstein & Haber, 1975; Oyama, Kikuchi, & Ichihara, 1981). The fact that there is a slope, even in the so-called "subitizing range," has been interpreted by some authors as indicating that the subitizing process cannot be dissociated from counting. Gallistel and Gelman (1992), for instance, postulated that subitizing involves a serial, albeit preverbal, counting mechanism, with nonverbal counting being faster than verbal counting. If subitizing is a serial

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process, then spatial attention would be required to locate all elements in the display, and visual pointing would not be ruled out.

In contrast, there are several models based on the assumption that the slight slope of the subitizing range curve does not reflect a serial process, and that up to five elements (more or less, depending on factors such as practice and spatial arrangement), a parallel perceptual process is used to evaluate quantity (Butterworth, 1999; Dehaene, 1997; Sathian et al., 1999; Trick & Pylyshyn, 1993, 1994). According to these models, participants do not count each item individually, but perceive small quantities globally and immediately, without any manual or ocular pointing. In this view, subitizing is a parallel process. In Dehaene and Changeux's (1993) normalization model and in Allik and Tuulmets's (1991) estimation model, subitizing is seen as a precise estimation (i.e., as a fast, number-dependent quantification process). In Trick and Pylyshyn's (1993, 1994) "fingers of instantiation" model (FINST), subitizing relies on "mental reference tokens," and the limited number of tokens explains the subitizing limit. Others suggest that when subitizing, participants use configuration recognition to extract numerosity (Mandler & Shebo, 1982; von Glasersfeld, 1982; Wender & Rothkegel, 2000; Wolters, van Kempen, & Wijlhuizen, 1987). According to von Glasersfeld (1982), before learning to count, children form a semantic link between the name of a quantity, the "number word" pronounced by the adult, and the spatial configuration of that quantity. The relative stability of small configurations allows children to immediately associate a "number word" with its corresponding configurations (e.g., two is always a line, three is most often a triangle; Mandler & Shebo, 1982). The subitizing limit would thus be due to the fact that the number of possible configurations increases with the number of elements, and only regular configurations, such as canonical dice patterns, could extend the subitizing limit. More recent models that also recognize the importance of configuration recognition in subitizing are based on the idea that subitizing requires memory (Camos, 2003; Peterson & Simon, 2000). According to these models, when the number of items in a configuration (canonical or not) is evaluated, the association between the configuration and the "number word" is stored in working memory. Each subsequent presentation of the configuration reinforces its trace in long-term memory, and at some point, the "number word" can be immediately associated with the configuration (subitizing). Thus, whereas according to Gallistel and Gelman's (1992) model, counting and subitizing are two different levels along a continuum of complexity of the same mechanism, according to the second group of hypotheses, they are two qualitatively different and separable processes. Understanding the factors underlying CP children's low subitizing limit might help answer this question.

Immediate grasping of small numerosities has been observed in animals (Murofushi, 1997) as well as in humans, even at a very young age (Antell & Keating, 1983), suggesting an ability to abstract numerical invariance from small-set visual arrays as early as the first week of life. Although subitizing is considered to be based on an innate capacity, learning and age increase both its speed, from about 195 ms to 40 ms per added element (Chi & Klahr, 1975; Svenson & Sjoeberg, 1983), and its limit: During childhood, the upper limit of subitizing goes from 3 to 5, which represents the normal limit for adults (Starkey & Cooper, 1995). To our knowledge, the observation that subitizing might be impaired in CP children was the first to associate subitizing impairment to a developmental disorder (Arp & Fagard, 2001).

Cerebral palsy is a neuromotor developmental disorder caused by a brain lesion in the motor-control system that occurred before birth or during the first year of life. The lesion is stable and often concerns white fibers (periventricular leucomalacia). Cerebral palsy affects the child's motor development to various degrees and in different ways depending on the site of the lesion (pyramidal, extrapyramidal, or cerebellar). CP children may suffer from monoplegia to tetraplegia, either spastic, athetoid, ataxic, or mixed. Although intelligence is not always impaired in cerebral palsy, cognitive development is often affected. Cognitive delay is frequently attributed to disturbances in the ocular sensorimotor system. In fact, disturbances in visual maturation, subnormal visual acuity, visual field defects, and deficiencies in ocular motility and spatial scanning often affect premature CP children (Fedrizzi et al., 1998; Leat, 1996; Mayberry & Gilligan, 1985; Mazeau, 1998; Menken, Cermak, & Fisher, 1987). These deficiencies have a negative impact on CP children's achievement in school. This has been noted in particular in mathematics (De Barbot, Meljac, Truscelli, & Henri-Amar, 1989; Lacert, 1991; Mazeau, 1989; Temple, 1995), and a counting deficiency has been found to be correlated with eye–hand coordination impairment and a manual control disability (Arp & Fagard, 2001; Camos et al., 1998). Whereas it may seem logical that the lack of visuomanual control perturbs the development of counting, the factors responsible for the perturbation of CP children's subitizing are not clear.

One study (Arp, 2004) showed that CP children can use subitizing, but only up to a lower limit than control children of the same age. In this study, a relationship was found between the CP children's subitizing limit and their counting ability (Arp, 2004), suggesting that subitizing is not distinct from the serial process of counting; however, it also could be argued that subitizing is a parallel process involving a precise estimation based on the extraction of numerosity (Dehaene & Changeux, 1993), and that the mathematical nature of the task has a negative effect on its limit in CP children (''mathematical deficit'' hypothesis). Alternately, one could consider that subitizing is a parallel process based on configuration recognition, and that the lack of visuospatial routines provided by counting experience affects the subitizing limit, as suggested by Klein and Starkey (1987) (''visuospatial deficit'' hypothesis). To test these hypotheses, we compared CP children on two tasks: (a) a classic subitizing task in which a numerical answer was explicitly required of the child and (b) a pattern recognition task based on the number of dots, but in which the answer explicitly required was not a number but the name of the pattern. If CP children's difficulty in subitizing is rooted in the explicit reference to number, and thus from the mathematical nature of the task, then they should be impaired on the classic subitizing task more than on the pattern recognition task where the reference to numbers is only implicit. If CP children are disadvantaged to roughly the same extent in the two tasks, then this would indicate that CP children's difficulty in subitizing comes from a perturbation in the ability to immediately discriminate an array of simultaneously presented items; this would support the hypothesis of the lack of visuospatial routines. The lack of visuospatial routines could stem from impairment in visuospatial short-term memory, where the configurations are remembered. Visuospatial short-term memory, which is one facet of working memory, is used to store visuospatial information for 1 or 2 s (Baddeley, 1986) and either associate that information with a configuration already stored in long-term memory or create a new unit in long-term memory. We therefore tested the participants' visuospatial short-term memory (VSSTM) and visual short-term memory (VSTM). If subitizing is based on configuration recognition, then VSSTM deficiencies should have more effect on the subitizing limit than VSTM deficiencies.

We also checked the available files of the CP children to see whether their results could be related to lesion location. Since the right hemisphere has been shown to be involved in subitizing (Jackson & Coney, 2004), we hypothesized that different types of lesions should be reflected in the subitizing task results.

METHOD

Participants

Two groups of children were tested: a CP group and a control group. The CP group consisted of 44 CP children divided into two age groups: twenty 4- to 6-year-olds ($M = 5$ years 11 months, $SD = 9$ months) and twenty-four 7- to 9-year-olds ($M = 8$ years 0 month, $SD = 9$ months). Their handicaps are described in Table 1. Most of the children were born premature, as is often the case with CPs. Information about the number of gestational weeks (GW) was obtained for 40 of the CPs. Three degrees of prematurity were distinguished: very premature (27–30 GW, $n = 18$), premature (31–37 GW, $n = 18$), and term ($\geq$38 GW, $n = 4$). Concerning the lesion site, magnetic resonance imaging (MRI) results were available for 38 of the 44 children. Lesions were located at the following sites: parietal, occipital, or frontal; they were on the right and/or left side (see Table 1). Children were evaluated for verbal IQ, but not for performance IQ, which is impossible to assess in CP children most of the time. Only children with a verbal IQ of 70 or above and those who could use verbal language participated in the study. The verbal IQ for these

Table 1. Description of CP Participants (number of children in each case)

Topographic Disability	Level of Manual Disability**	Lesion Site*	Lesion Side	Corpus callosum	Ocular Pursuit (c/s)
Diplegia: 19					
	I: 4	P: 4, O: 5, F: 1	Right: 5	Thinning: 5	$\geq$0.8: 13
Hemiplegia: 3					
	II: 10	P-O: 7, P-F: 2	Left: 4	Normal: 34	$0.6 \leq \times < 0.8$: 10
Triplegia: 1					
	III: 13	O-F: 1, P-F: 1	Bilateral: 24	No data: 5	$\leq$0.4: 21
Tetraplegia: 21					
	IV: 9	P-O-F: 3	Normal: 5		
Tonus type	V: 7	Normal: 5	No data: 6		
Spasticity: 41					
Dystonia: 1		No data: 15			

*P = parietal lesion, O = occipital lesion, F = frontal lesion.
**Level of manual disability: According to this classification system, Level I indicates few limitations and Level V, severe impairment.

two groups was between 70 and 128 ($M = 93.5$, $SD = 18.05$). We were provided with orthoptists' reports. Visual impairments such as strabismus, visual field limitation, and fixation and ocular pursuit difficulties, common among CP children, were present in some of our children. The orthoptist was present before testing to ensure that the setting allowed the children to see the whole screen despite their visual difficulties. CP children with hemineglect were not selected for this study.

The control group consisted of 22 children divided into two age groups: ten 4- to 6-year-olds ($M = 5$ years 9 months, $SD = 10$ months) and twelve 7- to 9-year-olds ($M = 8$ years 0 month, $SD = 8$ months). All control children were free from manual or visual impairments.

All participants were French and were recruited and observed at their school, whether regular or located in a hospital, after we received a written agreement from the different levels of each institution (academic head and medical staff). Written informed consent was obtained from all parents for testing and from the CP children's parents for consulting the medical records.

PROCEDURE

All children were tested on two tasks in which the reference to quantity was either explicit (classic subitizing task) or implicit (pattern recognition task). In addition, they were given one test to assess their VSSTM span and one test to assess their VSTM span. All tasks were videotaped. A mirror was placed behind the child to reflect the computer screen. A camera placed next to the computer recorded the child's face and the mirror. We used videotaping to ensure that the child really looked at the screen during item exposure, to be able to see the child's eye movements or other counting strategies, and to assess the end of item presentation and the beginning of answer articulation to calculate response time. All tasks were presented in three different sessions of 15 to 20 min, separated by 1 or 2 days within the same week. During the first session, the classic subitizing task was presented first followed by the first pattern recognition learning stage. During the second session, children's VSSTM span and VSTM span were evaluated, followed by the second pattern recognition learning stage. During the last session, children underwent the third pattern recognition learning stage before being tested on the pattern recognition task.

Classic Subitizing Task

The classic subitizing task was presented on a computer. It was an explicit quantity evaluation task in which the children were required to say "how many marbles appeared." The task was composed of 33 items. The items, each comprising one to six marbles, were presented briefly (250 ms) on the screen to the child who was seated approximately 60 cm away. We chose a duration that prevented the children from reciting the counting rhyme (Case, Kurland, & Goldberg, 1982; Chi & Klahr, 1975). The items were presented in a 20×20 cm white square in two different arrangements of configuration: random or canonical (see Figure 1). We introduced this variable to compare subitizing when the pattern factor was salient (canonical) and when it was not. The "marbles" were 2 cm in diameter, with a minimum of 1.5 cm between them. Except for Quantity 1 (presented three times total), all quantities were presented three times in each arrangement (random and canonical). The presentation order for arrangement of configuration and quantity was the same pseudorandom order for all participants. The task lasted about 10 to 15 min. An item was not displayed until the child's attention was focused on the fixation point. None of the children made eye movements during the presentation of the items.

The dependent variables were accuracy and response time. We calculated two subitizing limits, one for the random arrangement (Sub-R) and one for the canonical arrangement (Sub-C). The subitizing limit was equal to the highest number for which the participant gave a correct answer immediately after presentation. We analyzed the percentage of correct answers for each quantity and each participant.

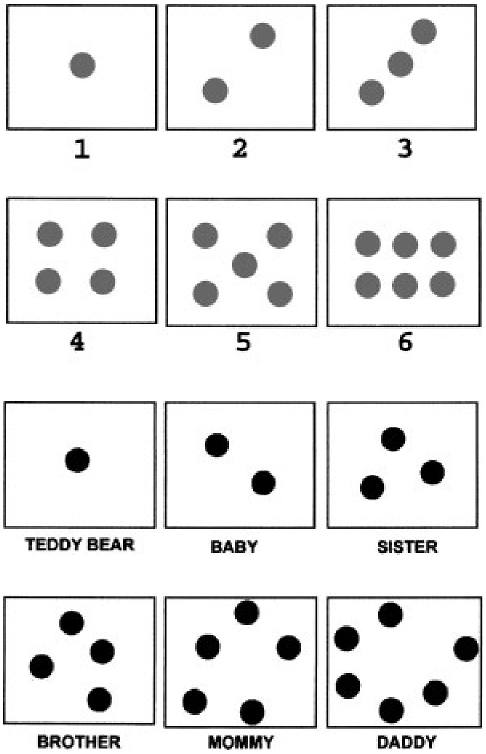

FIGURE 1 Canonical (subitizing task, top) and random (PR task, bottom) arrangements (the random arrangement was the same for the subitizing task).

Pattern Recognition Task

The pattern recognition (PR) task included three learning stages (pattern recognition learning, PR-L), one during each session, followed by a test at the end of the third session (pattern recognition test, PR-T).

PR-L. In this stage, the children had to learn the name of six patterns made up of one to six dots in an arrangement corresponding to the random condition in the classic subitizing task. The experimenter presented the six patterns on the same sheet of paper and taught the children their names. We gave each pattern a name that represented its size, without mentioning this analogy to the participants: The names were ‘‘papa’’ (French for daddy), ‘‘maman’’ (mommy), ‘‘frère’’ (brother), ‘‘soeur’’ (sister), ‘‘bébé’’ (baby), and ‘‘doudou’’ (teddy bear), for the six-, five-, four-, three-, two-, and one-dot patterns, respectively (see Figure 1). Nothing was mentioned about the number of dots, and the child's attention was focused on the pattern of each configuration. The child was asked to repeat the name associated to each pattern. Name recall was then tested four times for each pattern, with the experimenter reminding the child of the names if he or she failed to recall them. The experimenter ended the first two learning stages by naming each pattern once more. The children were considered to have successfully learned the name of all patterns if they were able to name each one twice without error at the end of the third learning session. Each learning stage lasted about 5 to 7 min. The one-dot pattern was presented (although the analysis did not include it) to ensure that the child could discriminate a one-dot from a two-dot pattern.

PR-T. All children who were able to learn the name of the six patterns took the PR-T in the same conditions as the subitizing task. Each pattern was presented on the screen three times for 250 ms, in the same pseudorandom order for all participants. Thus, the PR-T was composed of 18 items. Participants were asked to say ‘‘who appeared on the screen.’’ The PR-T lasted about 7 to 10 min. The dependent variable was the percentage of correct answers.

VSTM

The VSTM span of each child was equal to the number of colors the child could recall immediately after their visual presentation. (We checked first to make sure that the child knew the names of all the colors used.) The number of colors presented increased from two to six, and each quantity was presented twice. Each color appeared for 1 s and was masked by the color that followed. The test was stopped when two errors were made on the same quantity, and the last quantity recalled without error was considered as the child's VSTM span. This evaluation lasted about 5 min.

VSSTM

Th VSSTM task was aimed at evaluating the abilities of the children to memorize the spatial locations of visual elements presented simultaneously. A 3×3 grid was display on a computer screen for 3 s. There were between one and six purple circles, each in a separate square of the grid. The children were told to memorize the positions of each circle. After a 1-s mask, they were asked to point to the squares on the empty grid where the circles had been. The number of circles increased across trials, and each quantity was presented twice in a random arrangement. The test was stopped after two errors on the same quantity, and the last quantity recalled without error was taken as the child's VSSTM span. The errors could concern the number of circles or their location. This test lasted about 5 min.

DATA ANALYSIS

We calculated a subitizing limit for each arrangement and each child. The subitizing limit is usually calculated from accuracy or response time. In this study, we used both criteria because when the participant answered after a long delay, he or she could have counted the balls from visual memory after their disappearance from the screen. First, we calculated the mean percentage of correct answers per quantity for each participant. We considered a quantity to be successfully recognized when the percentage of correct answers was 100%. For response time, the quadratic curve method frequently applied (Chi & Klahr, 1975; Mandler & Shebo, 1982; Tuholski, Engle, & Baylis, 2001) could not be used because no quadratic curve could be found for most of the CP participants' RT curve. Therefore, we used Student's *t* test on each pair of adjacent quantities to see whether a significant increase in response time could be found (RT increases of less than 250 ms, usually considered below the normal increment in counting, were not taken into account). The subitizing limit was thus the last quantity to be successfully recognized before the first significant increase in response time. When RT did not change significantly across the six quantities, only the percentage of correct answers was taken into account.

Statistical analyses were carried out using STATISTICA for Windows version 5.1 software (copyright StatSoft, 1998). In addition to ANOVAs, Student's *t* test, chi-square, and correlation analyses, which indicate whether the true (population) effect differs from zero, we also checked the effect size for each analysis. At the descriptive level, we looked at the effect size using Cohen's formula[1] (Cohen, 1977). For the post hoc analyses, we used Tukey's test when the group sizes were the same, or the Spjotvoll and Stoline test (a Tukey-type test for different-size groups).

[1]Cohen's formula $f^2 = \chi^2/(1-\chi^2) = [(k-1)/(n-k)]^*F$.

In the Results section, we present for each task (a) a general analysis of the two groups (CPs and controls) and of the two age groups within each one, (b) an analysis of the factors that could affect subitizing, and (c) an analysis of the lesion-site effect on the subitizing limit for the CP children. In addition, we carried out a differential analysis of the CP children grouped according to their performance on the tasks.

RESULTS: GENERAL ANALYSES

Subitizing Task

Subitizing Limit. A $2 \times 2 \times 2$ (Group $\times$ Age $\times$ Arrangement) ANOVA was performed on the subitizing limit, with group and age as between-group factors and arrangement as a within-group factor. There was a significant main effect of group, $F(1, 62) = 19.10$, $p < .001$, of age, $F(1, 62) = 13.06$, $p < .001$, and of arrangement, $F(1, 62) = 71.72$, $p < .001$. The CPs had a lower subitizing limit than the controls, the younger children had a lower subitizing limit than the older ones, and the subitizing limit was lower on random than on canonical arrangements (see Table 2). The group effect was large ($d = 1.05$ for random arrangements; $d = 0.85$ for canonical arrangements); the age effect was large for random arrangements ($d = 1.04$) and medium-sized for canonical arrangements ($d = 0.78$); finally, the arrangement effect was large ($d = 1.02$).

The ANOVA yielded no significant interactions; however, the Group $\times$ Age $\times$ Arrangement interaction was close to reaching significance ($p < .06$): A post hoc analysis indicated a significant difference between random and canonical arrangements for each subgroup except for the 4- to 6-year-old CP children. Also note that there was no significant difference between the subitizing limit of the 7- to 9-year-old CP children and the 4- to 6-year-old controls.

A further analysis (Hierarchical Cluster Analysis) showed that 15 CP children (34%) had a normal subitizing limit as compared with their age-matched control group (three 4- to 6-year-olds and twelve 7- to 9-year-olds).

Table 2. Mean Subitizing Limit in Each Subgroup (and *SD*)

Group		Random	Canonical
CP	4 to 6-year-olds ($n = 20$)	2.25 (0.79)	2.95 (1.73)
	Efficient ($n = 3$)	3 (0)	6 (0)
	Nonefficient ($n = 17$)	2.12 (0.78)	2.41 (1.23)
	7 to 9-year-olds ($n = 24$)	3.08 (0.72)	4.63 (1.47)
	Efficient ($n = 12$)	3.50 (0.67)	5.83 (0.58)
	Nonefficient ($n = 12$)	2.67 (0.49)	3.49 (0.99)
Control	4 to 6-year-olds ($n = 10$)	3.10 (0.74)	5.00 (1.63)
	7 to 9-year-olds ($n = 12$)	3.92 (0.51)	5.42 (0.90)

We called these children "efficient." For each subsequent analysis, we systematically looked for a difference between the 7- to 9-year-old "efficient" CP children, the "nonefficient" CP children, and the same-age controls. (Given the small number of 4- to 6-year-old efficient CP children, the 4- to 6-year-olds were excluded from these analyses.) A 3 (Group: efficient CP group, nonefficient CP group, and control group) $\times$ 2 (Arrangement) ANOVA on the subitizing limit was conducted, with group as a between-group factor and arrangement as a within-group factor. We checked only for the main group effect and the interaction. The main group effect was significant, $F(2, 33) = 36.45$, $p < .001$, and large ($f^2 = 2.21$, $d = 1.19$). A post hoc analysis showed that the group effect was due to the difference between nonefficient CPs and the other two groups, but there was no difference between efficient CPs and controls (see Table 2). In addition, we found a significant Group $\times$ Arrangement interaction, $F(2, 33) = 8.30$, $p < .002$. A post hoc analysis showed that the arrangement effect was nonsignificant for the nonefficient CPs and significant for the other two groups.

Percentage of Correct Answers as a Function of Quantity and Arrangement of Configuration of Marbles. The percentage of correct answers on the subitizing task was analyzed to compare the performance on this task with the performance on the PR task, on which, contrary to the subitizing task, no "subitizing" or "global perception" limit[2] could be calculated. A $2 \times 2 \times 5 \times 2$ (Group $\times$ Age $\times$ Quantity $\times$ Arrangement) ANOVA was performed on the percentage of correct answers, with group and age as between-group factors and quantity and arrangement as within-group factors. Only the quantity effect and significant interactions with quantity are reported here since the other effects were similar to those observed in the subitizing limit analysis. A significant main effect was found for quantity, $F(4, 248) = 59.88$, $p < .001$, showing that accuracy decreased with increasing quantity. In addition, there was a significant Quantity $\times$ Group interaction, $F(4, 248) = 7.19$, $p < .001$: The quantity effect was significant only for CP children (pairwise comparisons of quantities). A significant Quantity $\times$ Age interaction was found, $F(4, 248) = 4.90$, $p < .001$: Performance decreased significantly with quantity only for 4- to 6-year-olds. A significant Quantity $\times$ Arrangement interaction also was found, $F(4, 248) = 11.45$, $p < .001$: The quantity had more effect on performance on random than on canonical arrangements (see Figure 2).

To discover whether the efficient CP children differed from the nonefficient ones, a $3 \times 2 \times 5$ (Group $\times$

[2]We could not calculate a "global perception" limit for the PR-T because the RTs were quite irregular, probably due to the fact that learning was recent.

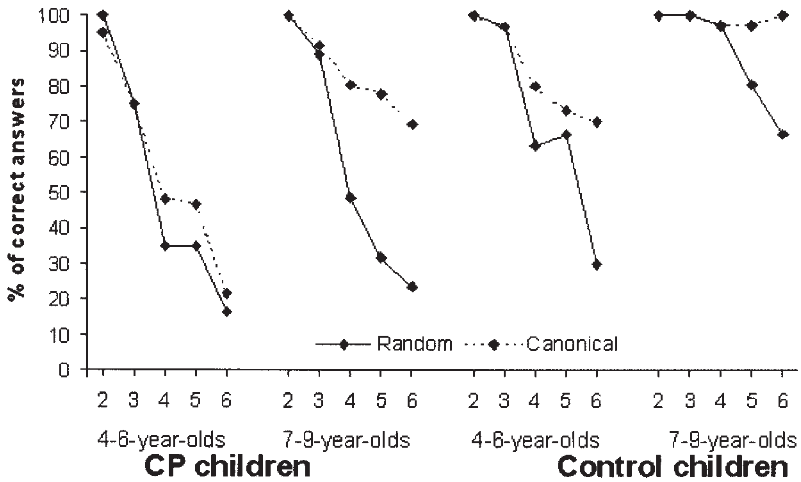

FIGURE 2 Mean percentage of correct answers on the subitizing task, as a function of arrangement and quantity, for each group and age.

Arrangement × Quantity) ANOVA was computed for the percentage of correct answers on the subitizing task, with group as a between-group factor and arrangement and quantity as within-group factors. We checked only for the main group effect and interaction involving groups. There was a significant group effect, $F(2, 33) = 18.47$, $p < .001$. A post hoc analysis showed that the effect was due to the difference between nonefficient and the other two groups, and was large ($f^2 = 1.12$). All interactions were significant (Group × Arrangement, $F(2, 33) = 7.53$, $p < .002$, Group × Quantity, $F(8, 132) = 8.53$, $p < .001$, and Group × Arrangement × Quantity, $F(8, 132) = 4.44$, $p < .001$. Post hoc analyses showed that the significant Group × Arrangement interaction was due to the difference between nonefficient and efficient CPs, and between efficient CPs and controls on random arrangements, but only between nonefficient and the other two groups on canonical arrangements. In other words, when all correct answers were considered (even those with too-long RTs to be classified within the subitizing range), the efficient CPs differed from the controls on random but not on canonical arrangements. In both arrangements, the efficient CPs were better than the nonefficient ones, and the efficient CPs, unlike the nonefficient ones, showed a real positive impact of the canonical arrangement on performance. Post hoc analyses of the Group × Arrangement × Quantity effects showed that on random arrangements, the quantity effect (pairwise quantity comparison) was significant for nonefficient and efficient CPs, but not for controls; on canonical arrangements, the significance disappeared for efficient CPs[3] (see Figure 3).

[3]No relationship was observed between the CP children's subitizing limit and their verbal IQ. There was no effect of prematurity, level of manual disability, and strabismus on the subitizing limit; however, all efficient CPs had an ocular pursuit close to the normal range (range = 0.8 c/s; $\chi^2(2, N = 23) = 6.67$, $p < .03$).

PR Task

PR-L. During the PR-L stages, none of the children counted explicitly the dots in the configuration. Thirteen CP children (29.5%) and only 1 control (0.05%) were unable to learn the names of the six patterns. Nine of these CP children were 4- to 6-year-olds, and 4 were 7- to 9-year-olds. These children will hereafter be called "partial," as opposed to "nonpartial." All the efficient CP children were able to learn the names of the six patterns.

PR-T. This analysis concerned only the nonpartial children. We looked at the percentage of correct answers for each pattern. A 2 × 2 × 5 (Group × Age × Pattern) ANOVA was performed on the percentage of correct answers, with group and age as between-group factors and pattern as a within-group factor. Significant main effects were observed for group, $F(1, 48) = 30.21$, $p < .001$, and for pattern, $F(4, 192) = 12.97$, $p < .001$, but not for age. CP children had a lower percentage of correct answers than control children. This effect was large ($d = 1.66$). The percentage of correct answers decreased as the number of dots in the pattern increased, except for the six-dot pattern, for which accuracy increased. The only significant interaction was a Group × Pattern interaction, $F(4, 192) = 4.30$, $p < .002$. A post hoc analysis showed that only CP children's accuracy decreased significantly as the number of dots in the pattern increased (see Figure 4). Both groups showed a noticeable increase in the percentage of correct answers on the six-dot pattern. This may be due to the fact that on this task, the children could respond "daddy" on the basis of a simple judgment of the "biggest" array.

Comparison of the Two Tasks

To investigate the factors likely to be responsible for the low subitizing limit of CP children, we first checked for

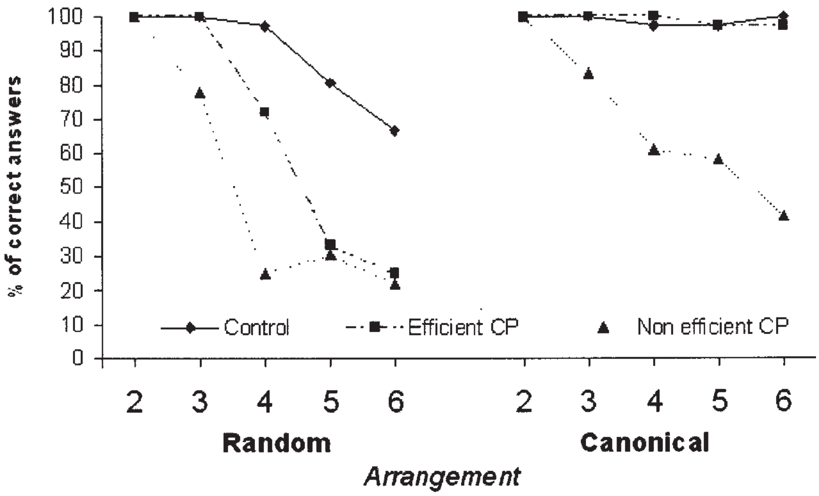

FIGURE 3 Mean percentage of correct answers on the subitizing task, as a function of arrangement and quantity, for each group (efficient CP, nonefficient CP, and control).

the effect of the answer (numerical or nonnumerical) on the ability to immediately discriminate small arrays of items. To compare the percentage of correct answers in the two groups on the two main tasks, a $2 \times 2 \times 2 \times 5$ (Group $\times$ Age $\times$ Task $\times$ Quantity) ANOVA was performed with group and age as between-group factors and task and quantity as within-group factors. The dependent variables were the correct-answer percentages on the subitizing task with random arrangements and on the PR task. (Our analysis was limited to the comparison between the random condition of the subitizing task and the PR task since the latter was presented only in the same random arrangements as the former.) Obviously, partial children, who had been unable to learn all the patterns in the PR-L task, could not be included in this analysis. Only the main task effect and the interactions in which the task variable was involved are reported here. A significant main effect of task was found, $F(1, 48) = 13.72, p < .001$: Overall, the PR task was performed better than the random subitizing task (80.56 vs. 70.49% correct answers for the PR task and random subitizing tasks, respectively); however, this effect was small ($d = 0.48$). There was a significant Task $\times$ Quantity interaction, $F(4, 192) = 17.99, p < .001$. A post hoc analysis showed that the task effect on performance was significant only for the quantity 6, for which the percentage of correct answers decreased on the classical subitizing task but increased on the PR-T, as discussed earlier. The Task $\times$ Group interaction was nonsignificant, suggesting that CP children were disadvantaged to the same extent in both tasks (percentage of correct answers: 59.85% for CP children vs. 81.11% for control children in random subitizing task, 68.44% for CP children vs. 92.69% for control children in PR-T).

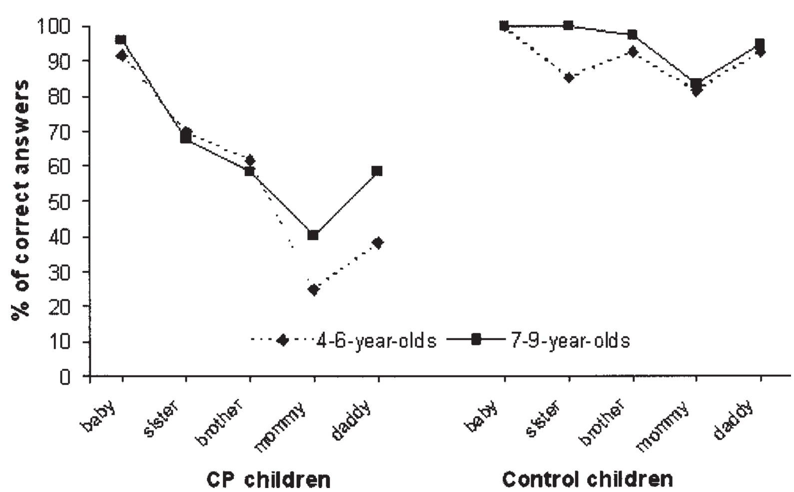

FIGURE 4 Mean percentage of correct answers as a function of pattern.

We looked into whether the partial CP children differed from the other CP children on the subitizing task. To do so, we conducted a 2 × 2 × 2 (Group: partial, nonpartial × Age × Arrangement) ANOVA on the subitizing limit with CP group and age as between-group factors and arrangement as a within-group factor. Only the main effect of CP group and interactions involving the CP group variable are reported. There was a significant CP group effect, $F(1, 40) = 29.72$, $p < .001$. The partial CP children of both age groups had a lower subitizing limit than the nonpartial CP children. This effect was large ($d = 1.41$ on random arrangements, and $d = 2.05$ on canonical arrangements). A significant CP Group × Arrangement interaction was found, $F(1, 40) = 13.66$, $p < .001$. Canonical arrangements resulted in a higher subitizing limit than random arrangements for the nonpartial CP children only (4.48 vs. 2.90 for nonpartial CP children on canonical and random arrangements, respectively; 2.14 vs. 2.07 for partial CP children on canonical and random arrangements, respectively).

In addition, we checked to see whether the efficient CP children (as defined on the subitizing task) differed from the nonefficient CP children who could learn the six patterns on the PR-T. (Remember that all the efficient CP children were able to learn the names of the six patterns.) A 3 × 5 (Group: efficient CPs, nonefficient CPs, and controls × Pattern) ANOVA was computed on the percentage of correct answers, with group as a between-group factor and pattern as a within-group factor. Only the main effect of group and interactions involving the group variable are reported. We found a significant group effect, $F(2, 29) = 16.20$, $p < .001$, and a significant Group × Pattern interaction, $F(8, 116) = 4.98$, $p < .001$. Post hoc analyses showed that the efficient CP children performed better on the PR-T than the nonefficient ones, but worse than the control children (see Figure 5). This effect was large ($f2 = 1.12$). As opposed to the nonefficient CPs, the efficient CPs and the controls exhibited no significant decrease in performance as the number of dots in the pattern increased from one to five. This result indicates that the efficient CP children were able to use a gestalt-based procedure to learn dot configurations while the nonefficient CP children were not.

It appears, then, that many CP children (29 of 44, 66% of our CP group) are handicapped in discriminating a gestalt when briefly presented with an array of dots, regardless of whether the answer to be given is explicitly numerical. What factors affect the subitizing limit?

FACTORS INFLUENCING SUBITIZING

For each factor, we report three analyses: (a) a general analysis of the factor, (b) a correlation between this factor and the subitizing limit, and (c) a differential analysis comparing efficient CP children, nonefficient CP children, and control children.

VSTM Task

A 2 × 2 (Group × Age) ANOVA was performed on the VSTM span with group and age as between-group factors. Significant main effects were found for group, $F(1, 62) = 21.84$, $p < .001$, and age, $F(1, 62) = 8.97$, $p < .004$. CP children had a lower VSTM span than did control children, and the observed effect was large ($d = 1.17$; see Table 3). The younger children had a lower VSTM span than the older ones; this effect was medium-sized ($d = 0.70$). There were no significant interactions.

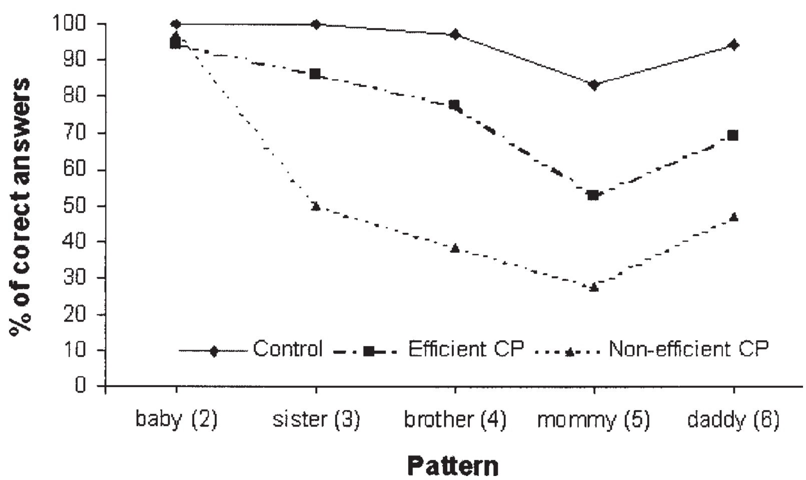

FIGURE 5 Mean percentage of correct answers on the PR-T, as a function of pattern in each group (efficient CP, nonefficient CP, and control). Only nonefficient children who could learn the six patterns were tested.

Table 3. Mean Visual Short-term Memory (VSTM) Span and Visuospatial Short-term Memory (VSSTM) Span (and *SD*)

Group		VSTM	VSSTM
CP	4 to 6-year-olds	2.05 (0.89)	2.80 (1.10)
	7 to 9-year-olds	2.79 (0.88)	3.54 (1.67)
Control	4 to 6-year-olds	3.20 (1.14)	5.00 (1.41)
	7 to 9-year-olds	3.92 (0.90)	5.83 (0.58)

For each group, a Bravais-Pearson partial correlation between VSTM span and subitizing limit was calculated for each arrangement (random and canonical) with age partialed out. A significant relationship was observed between VSTM span and the subitizing limit on random arrangements and between VSTM span and the subitizing limit on canonical arrangements for CP children ($pr = .33$, $p < .05$, and $pr = .51$, $p < .001$, respectively), but not for control children. In the CP group, the larger the VSTM span, the higher the subitizing limit on random as well as on canonical arrangements. The first of these two effects was medium-sized ($r^2 = 0.11$), and the second was large ($r^2 = 0.26$).

No significant difference was observed between efficient and nonefficient CPs on the VSTM task (Remember that only 7- to 9-year-olds were analyzed for efficiency.), and both groups had a lower VSTM span than control children, $t(22) = 2.57$, $p < .02$, and $t(22) = 3.65$, $p < .002$, respectively. These effects were large ($d = 1.09$ and $d = 1.56$, respectively).

VSSTM Task

A 2 × 2 (Group × Age) ANOVA was performed on VSSTM span, with group and age as between-group factors. It revealed significant main effects of group, $F(1, 62) = 36.94$, $p < .001$, and age, $F(1, 62) = 4.82$, $p < .03$. CP children had a lower VSSTM span than control children, and the effect was large ($d = 1.68$).[4] Younger children had a lower VSSTM span than older children, but the effect was small ($d = 0.46$; see Table 3).

For each group, a Bravais-Pearson partial correlation between VSSTM span and subitizing limit was calculated for each arrangement (random and canonical) with age partialed out. No significant relationships were found between VSSTM span and the subitizing limit on random arrangements for both groups. In contrast, there was a significant relationship between VSSTM span and the subitizing limit on canonical arrangements for the CP group, $r = .60$, $p < .001$, but not for control children. The larger the CP children's VSSTM span, the higher their subitizing limit on canonical arrangements. This effect was large ($r^2 = 0.36$).

The differential analysis showed that the efficient CP children had a larger VSSTM span than nonefficient CP children (4.67 vs. 2.42), $t(22) = 4.46$, $p < .001$. This effect was large ($d = 1.90$). In turn, the efficient CP children had a lower VSSTM span than the control children (4.67 vs. 5.83), $t(22) = 2.97$, $p < .01$. This effect was medium-sized ($d = 0.75$).

Impact of Lesion Location on Subitizing

An ANOVA on the subitizing limit as a function of the lesion site (parietal, occipital, or frontal) did not reveal any significant effects. In contrast, the lesion side turned out to be a relevant factor. We distinguished four categories of participants, depending on the side of their lesion: right-hemisphere lesion ($n = 5$), left-hemisphere lesion ($n = 4$), bilateral lesion ($n = 24$), or no apparent lesion ($n = 5$). A 4 × 2 (Lesion Side × Arrangement) ANOVA was performed on the CP children's subitizing limit with lesion side as a between-group factor and arrangement as a within-group factor. A significant main effect was found for lesion side, $F(3, 34) = 4.70$, $p < .01$. This effect was large ($f^2 = 0.41$). A post hoc analysis showed that the children with a right-hemisphere lesion or with a bilateral lesion had a lower subitizing limit than the children with a left-hemisphere lesion or with no apparent lesion (subitizing $M = 2.70$, 2.94, 4.50, and 4.20 for right-hemisphere, bilateral lesion, left-hemisphere, and no lesion, respectively). There was no significant subitizing-limit difference between the right-hemisphere and the bilateral lesion children, and no significant difference between the left-hemisphere and the no apparent lesion children. The Lesion Side × Arrangement interaction was significant, $F(3, 34) = 3.86$, $p < .01$. A post hoc analysis showed that the lesion-side effect was significant only on canonical arrangements. As seen in Figure 6, the subitizing limit of the CP children with a right-hemisphere lesion (either isolated or in conjunction with a left-hemisphere lesion) is clearly lower than the subitizing limit of the CP children without a right-hemisphere lesion.

Finally, only a few of the efficient CP children had a right-hemisphere or bilateral lesion, contrary to the nonefficient CP children ($n = 3$ of 8 vs. 11 of 13 for efficient and nonefficient CP children, respectively; $\chi^2_{(2)} = 6.91$, $p < .03$); this effect was large ($r^2c = 0.29$). Thus, a lesion including the right-hemisphere seems to be associated with a subitizing deficiency.

DISCUSSION

The goal of this study was to investigate what impairs subitizing in CP children. By comparing CP children with

[4]Fine-grained analyses of the VSSTM task showed that the CP children's errors were on the spatial location of the circles rather than on their number.

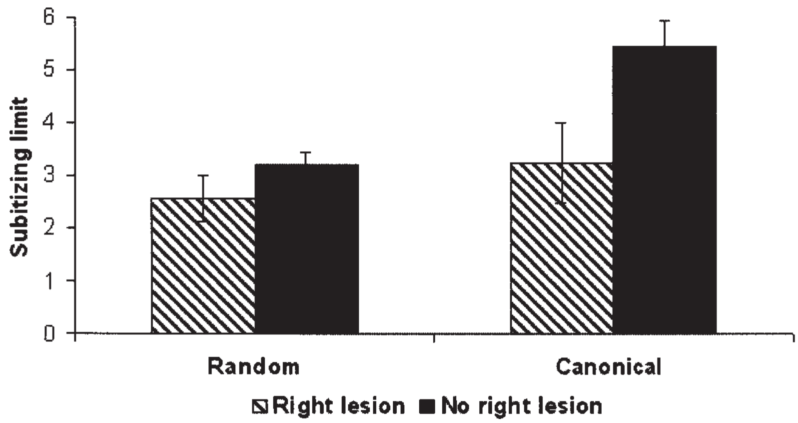

FIGURE 6 Mean subitizing limit as a function of arrangement and lesion location.

same-age control children on two similar tasks (rapid recognition of dot configurations) but in which the answer was either a number (subitizing task) or the name of a pattern (PR task), we hoped to learn whether the low subitizing limit of CP children was due to the explicit reference to numbers. Our results for the subitizing task showed that the CP children, as a group, had a significantly lower subitizing limit than the controls, and that canonical arrangements gave rise to a higher subitizing limit than random arrangements in both groups considered as a whole. In the CP and control groups alike, there was a significant increase in the subitizing limit with age, and no difference was observed between the subitizing limit of the 7- to 9-year-old CP children and that of the 4- to 6-year-old controls. These results are consistent with those of a previous investigation showing a lag in the development of subitizing in CP children as compared with control children (Arp, 2004); however, among the CP children, two subgroups could be distinguished: one (the largest) composed of CPs who had a significantly lower subitizing limit than controls (nonefficient), and one composed of CPs who had a subitizing limit comparable to controls (efficient). Among the CP children, only the efficient ones exhibited a real positive impact of canonical arrangements on performance, which was better, as it was for controls, than when the arrangements were random. The nonefficient CP children, in contrast, showed almost no impact of the arrangement. In addition, their performance decreased as a function of quantity in canonical as well as in random arrangements (as opposed to efficient CPs for whom there was a quantity effect only on random arrangements and to controls who showed no quantity effect at all).

For the PR-T, several CP children were unable to learn the names of the six patterns. The CP children who did learn these names had a lower percentage of correct answers than controls. In addition, CP accuracy decreased as the number of dots in the pattern increased, unlike the accuracy of the controls; this indicates that CPs did not use gestalt perception to recognize the pattern (for both groups, there was an increase in accuracy on the six-dot pattern, which we interpreted as reflecting a simple judgment of the ‘‘biggest’’ array).

Overall performance was better on the PR-T than on the subitizing task, but this held true for both groups and was due to the six-dot pattern. CP children did not do better (compared with same-age controls) on pattern recognition than on classic subitizing. The CP children were disadvantaged to the same extent on both tasks, suggesting that their difficulty in subitizing does not come from the explicit reference to number. In addition, partial children exhibited a lower subitizing limit on the classic subitizing task than the nonpartial children. All efficient CP children were able to learn the six patterns on the PR-T, and all performed better on the PR-T than the nonefficient nonpartial children. The decrease in performance as the number of dots in the pattern increased (up to five) interacted with the group: It was significant for the nonefficient CPs, nonsignificant for the efficient CPs, and absent for the controls. The fact that the nonefficient CPs exhibited a decrease in performance on the PR-T as the number of dots in the pattern increased, added to the fact that they were not better with a canonical arrangement (as compared with a random one) on the classic subitizing task, indicates that their difficulty using gestalts applies to both tasks and is not dependent on context. This indicates that subitizing depends on the ability to perceive a gestalt.

The finding that discriminating a gestalt played a clear role in determining the subitizing limit does not support the idea that subitizing is a serial process. The finding that CP children, when they were impaired, were impaired to the same extent whether or not the instructions was to quantify the number of dots does not support the hypothesis that the mathematical nature of the task has a negative effect on their performance. Rather, these results lend support to the hypothesis mentioned in the introduction as the ‘‘visuospatial deficit’’ hypothesis, suggesting that CP children’s visuospatial impairment hinders their perception and memorization of spatial configurations. Another goal of the study was to discover which factors are the most likely to influence this capacity in CP children.

CP children performed less well than control children in both of these visual-memory tasks, and performance in both groups increased with age. The CP children’s subitizing limit was correlated with VSTM for canonical and random arrangements, and with VSSTM for canonical arrangements only: the larger the span, the higher the subitizing limit. However, the efficient CP children differed from the nonefficient ones only on the VSSTM span and not on the visual span. The fact that the nonefficient CP children performed at a lower level than the efficient CPs and the controls on the visuospatial task and that the CPs VSSTM span was correlated with their subitizing limit on canonical arrangements suggests that a lower ability to detect and memorize the visuospatial characteristics of a stimulus may affect subitizing in CP children. However, this impairment may not be specific to subitizing since a short visuospatial memory span (along with a normal verbal memory span) has been observed in children suffering from dyscalculia (Strange & Rourke, 1985).

We found no effect of the lesion site on the subitizing limit, so the implication of the parietal lobe in subitizing, stressed by some authors (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Fink, Marshall, Halligan, & Dolan, 1999; Piazza, Giacomini, Le-Bihan, & Dehaene, 2003; Piazza, Mechelli, Butterworth, & Price, 2002; Sathian et al., 1999) was not found in our study, possibly because of the lack of precision of the MRI report. In contrast, it appears from our results that a right lesion increases the risk of disruption of the subitizing process, more so on canonical than on random arrangement, possibly because of the gestalt perception involved in the former. This finding supports the idea of right-hemisphere involvement in subitizing (Jackson & Coney, 2004; Pasini & Tessari, 2001). It also is interesting to relate our results to the visuospatial impairment observed in syndromes such as Williams syndrome, spatial agnosia, or ‘‘white fiber connection.’’ When presented with a pattern consisting of local elements, these subjects focus on the local elements and are unable to perceive the global pattern—a perturbation often interpreted as reflecting a right-hemisphere dysfunction (Rourke, 1989; Rourke & Conway, 1997).

In conclusion, these results suggest that the low subitizing limit of CP children, compared to same-age control children, stems from a lesser capacity to perceive a dot configuration as a gestalt. This lesser capacity of subitizing is not dependent on explicit instructions to report the quantity of dots of the configuration since it was observed to the same extent when the participants were not questioned about the numerosity of the configuration but about its name. A low subitizing limit was not observed in all CP children, and those CP children with a limit comparable to controls were better on the PR-T and had a better VSSTM span than the other CPs. In addition, a lesion that included the right hemisphere was less frequent among the former than among the latter. Finally, these results argue in favor of subitizing as a different process from serial counting, and support the ‘‘visuospatial deficit’’ hypothesis mentioned in the introduction.

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