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Spatial and numerical processing in children with non-verbal learning disabilities

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ABSTRACT

Consistently with the idea that numbers and space interact with each other, the present paper aimed to investigate the impact of non-verbal learning disabilities (NVLD) on spatial and numerical processing. In order to do so, 15 NVLD and 15 control children were required to perform different spatial (the line bisection and Simon tasks) and numerical tasks (the number bisection, number-to-position and numerical comparison tasks). In every task, NVLD children presented lower accuracy scores than the control group. While both groups manifested similar pseudo-neglect and Simon effects, they however differed in the numerical comparison task: while control children presented the standard SNARC effect in the uncrossed and crossed postures, no SNARC effect was observed in the NVLD group. Our results therefore suggest that NVLD affects the accuracy and the nature of the mental number line by decreasing its precision and the saliency of its left-to-right orientation.

1. Introduction

Historically, many mathematical advances have been developed through interactions between numbers and space. In cognitive psychology, research has shown that number and space processing interact with each other. The major evidence used to support this fact comes from the observation of some compatibility effects between number and space in behavioural forced-response paradigms. The so-called SNARC effect (Spatial Numerical Association of Response Codes) indicates that (in several Western cultures) small numbers are preferentially associated with a left-sided response whereas larger numbers are preferentially associated with a right-sided response (Dehaene, Bossini, & Giraux, 1993). The SNARC effect was often compared to the spatial Simon effect (the time to respond to a stimulus is faster and more accurate when the position of the stimulus is compatible with the side of the response: Simon, 1969; Simon & Rudell, 1967; Simon & Wolf, 1963) and was interpreted as an index of the spatial organization of the mental number line. According to this account, small numbers are responded to faster with left-sided responses and large numbers are responded to faster with right

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sided-responses because this stimulus–response association is congruent with the left-to-right orientation of the mental number line.

Evidence supporting the existence of an interaction between numbers and space also comes from studies using the line bisection task (Calabria & Rossetti, 2005; Fischer, 2001). In this task, participants tend to perceive a line midpoint to the left of its actual midpoint when this line is composed of small numbers (in Arabic as well as in verbal notation; pseudoneglect effect: Jewell & McCourt, 2000). Inversely, they tend to perceive the line midpoint to the right of its actual midpoint when the line is composed of large numbers. Number processing distortions have also been found in patients presenting hemi-spatial neglect, who typically tend to ignore the contralesional space (usually left) of their lesion (usually situated in the right parietal cortex). So, in a classic line bisection task, in which the midpoint of a physical line has to be indicated, they neglect the left portion of the line and then tend to displace the midpoint of the line towards the right. This hemi-spatial neglect has been shown to extend to the representation of numbers: patients systematically displace the actual midpoint of a numerical interval towards the right (i.e., the large numbers) when asked to bisect it (Hoeckner et al., 2008; Zorzi, Priftis, Meneghello, Marenzi, & Umilta, 2006; Zorzi, Priftis, & Umilta, 2002). However, when small physical lines or small numerical intervals are presented, a "cross-over effect" is observed, which means that, in this case, the bisection performances are deviated towards the left/the smaller numerical values. These spatial and numerical distortions can be improved by wearing prismatic goggles, thereby indicating that numbers and space are intrinsically connected (Rossetti et al., 1998, 2004).

The association between space and number has also been reported in children presenting developmental dyscalculia (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013) and in children suffering from non-verbal learning disabilities (NVLD) (Mammarella & Cornoldi, 2014; Nichelli & Venneri, 1995; Rourke, 1989). In the literature, NVLD has been associated with neuropsychological, academic and socio-emotional deficits (Rourke, 1989). However, in this paper, we will use the term NVLD to refer to children presenting major difficulties in areas of spatial skills[1] within a context of well-developed psycholinguistic skills (Rourke, 1989). This is in accordance with the name of the most widespread tool that is used to identify NVLD in schools: the Cornoldi's shortened visuo-spatial questionnaire (Cornoldi, Venneri, Marconato, Molin, & Montinari, 2003). This questionnaire is highly correlated to tasks specifically related to the NVLD problem (e.g., block design, corsi block span). However, by using the term visuo-spatial rather than the term NVLD, the authors (Cornoldi et al., 2003) wanted to highlight that the most salient characteristic of NVLD was a spatial processing problem.

In the numerical field, it has already been demonstrated that NVLD perform significantly worse than typically developing children in geometry (Mammarella, Giofrè, Ferrara, & Cornoldi, 2013) and in arithmetic tasks that require some visuo-spatial processes.[1] For example, in written calculation, they produce more borrowing and carrying errors than their control peers (Venneri, Cornoldi & Garuti, 2003), but also more partial calculation errors and column confusions (Mammarella, Lucangeli, & Cornoldi, 2010). In the same line, Vaivre-Douret et al. (2011) tested children with a developmental coordination disorder (often associated with low visuo-spatial skills) and found that 88% of the 43 children tested had school failures in mathematics, more particularly in geometry or while calculating sums in arithmetic. More recently, Crollen and Noël (2015) investigated whether visuo-spatial weaknesses in typically developing children may affect not only pure spatial processing but also basic numerical tasks tapping the number magnitude itself. Indeed, as a large number of studies have shown that the number magnitude representation could be coded on a spatial medium, the authors wanted to test whether visuo-spatial weaknesses could affect this representation. In their study, the performances of children with high and low visuo-spatial abilities were directly compared on different spatial (the line bisection and Simon tasks) and numerical tasks (the number bisection, number-to-position and numerical comparison tasks). While children from the low visuo-spatial group presented the classic pseudo-neglect, Simon and SNARC effects, they systematically showed larger deviation errors as compared to the high visuo-spatial group. The authors therefore concluded that low visuo-spatial abilities did not change the nature of the mental number line but led to a decrease in its accuracy.

In this paper, we wanted to further examine the spatial and numerical weaknesses that are associated to NVLD. Fifteen NVLD children and 15 control children were therefore required to perform the same spatial (the line bisection and the Simon tasks) and numerical tasks (number-to-position, number bisection and numerical comparison task to 5) as in Crollen and Noël (2015). These different tasks allowed us to investigate the impact of NVLD on the representations of space and numbers. First, we examined whether NVLD children presented the same pseudo-neglect, Simon and SNARC effects as their control peers. Second, by comparing the three numerical tasks, we examined whether NVLD impacted all numerical tasks or only impacted the task that requires the processing of external space, i.e., the number-to-position task. Finally, the last question relevant for our purposes was to investigate the impact of NVLD on the coordinate frame in which the SNARC and the Simon effects arise. Several findings already suggested that an effector independent representation of space was involved. It has indeed been demonstrated that the SNARC (Dehaene et al., 1993) and the Simon effects (Röder, Kusmierek, Spence, & Schicke, 2007) occur even when participants respond with the hands crossed over the body midline: small numbers (left-sided stimulus) continue to be associated with the left external space, even when responses on that side are made with the right hand. If NVLD does not affect the reference frame in which the SNARC and the Simon effects occur, children should present both effects in the uncrossed as well as in the crossed hands position. In contrast, if visuo-spatial difficulties prevent

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[1] Visuo-spatial processes are one component of our cognitive functioning that refers to our ability to process and interpret visual information about where objects are in space.

the development of the effector-independent frame of reference, NVLD children should not manifest the standard Simon and SNARC effects in the crossed position (Crollen, Dormal, Seron, Lelore, & Collignon, 2013; Röder et al., 2007).

2. Method

2.1. Participants

Fifteen children (14 boys, 4 left-handed) who were diagnosed as presenting a NVLD were recruited from reeducation centres in Belgium and in Paris (France). Participants were aged between 6 and 13 years old ($M = 10.3 \pm 2.05$). To be included in the study, children had to present, in addition to their NVLD diagnosis, a verbal intelligent quotient (VIQ) at least 10 points higher than the performance intelligence quotient (PIQ) (Mammarella & Cornoldi, 2014). None of the children presented additional neurological problems. Fifteen control children (14 boys, 3 left-handed) were then selected to match the NVLD children in terms of sex, VIQ and age ($M = 10.6 \pm 1.45$), $t(28) = -0.7$, $p > .4$. For several reasons, some participants had however to be excluded from some of the data analyses reported below. Supplemental Table 1 listed the final sample of participants that was analyzed in each task and the groups' statistics in terms of age and VIQ.

Supplementary Table 1 related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ridd.2015.08.013.

Written informed parental consent was obtained for all the children. Procedures were approved by the Research Ethics Boards of the Psychological Institute of the University of Louvain, Belgium.

2.2. Screening tasks

Seven screening tasks were presented to evaluate children's visuo-spatial performance and IQ. *The Cornoldi shortened visuo-spatial questionnaire* (Cornoldi et al., 2003) is a short (18 items) screening questionnaire that can be used in primary schools to identify children presenting a visuospatial learning disability. Parents of the children tested were required to fill this questionnaire during the testing session of their child. *The NEPSY design copying test* (Korkman, Kirk, & Kemp, 1998) measures motor and visuo-perceptive skills associated with the ability to copy 18 two-dimensional geometric figures. Each figure is evaluated by a score ranging from 0 to 4 but six points are removed from the total score (Korkman et al., 1998), giving a maximum score of 66. *The Rey Complex Figure Test* (Osterrieth, 1944) required participants to reproduce a complicated line drawing by copying it freehand. Different cognitive abilities are needed for a correct performance, and the test therefore permits the evaluation of different functions, such as visuospatial abilities, attention, and planning. The block design and the matrix reasoning subtests of the WISC-IV (Weschler, 2005) were used to evaluate children PIQ. In the *Block design test*, children had to put together red-and-white blocks in a pattern according to a displayed model. In the *matrix reasoning subtest*, children were shown an array of pictures with one missing square, and had to select the picture that fits the array from five options. The vocabulary and the similarity subtests of the WISC-IV were finally used to assess VIQ. *Vocabulary* required children to define a provided word. In the *Similarity* subtest, children had to say how two words were similar.

2.3. Experimental tasks

2.3.1. Line bisection task

The line-bisection task was composed of 18 horizontal black lines 1 mm wide presented on three different white sheets of paper (21 cm × 30 cm). Half of the lines measured 8 cm in length; the other half 16 cm. The lines were randomly positioned so that six lines appeared in the middle of the sheet, six lines appeared near the left margin, and six lines appeared near the right margin. The sheet was laid in front of the participant's midline. Participants were instructed to bisect all lines into two parts of equal length by marking the subjective midpoint of each line with a pencil. The experimenter covered each line after it was marked to ensure that participants were not biased by their previous choices. There was no time restriction. The subjective midpoints of each marked line were carefully measured. To examine whether responses presented a left or a right bias, the deviation score (DS) for each line was computed as follows: participant's half estimation – true half. Negative values indicated a left bias; positive values a right bias. To measure the precision of the responses, the absolute DS for each child and for each trial was also computed and then averaged across the scores for each child.

2.3.2. Number bisection task

Eighteen pairs of numbers were visually presented to the children. Six pairs contained a one- and a two-digit number (e.g., 8–15); twelve other pairs included two two-digit numbers (e.g., 59–64). The two numbers of the pair were presented to the left and to the right of a fixation cross. The numerical distance between each number was either 5, 7 or 9. The magnitude of the numbers presented was either small, medium or large (see Table 1 for a detailed description of the stimuli). Each number pair was presented twice, once in the ascending order (i.e., smallest number presented to the left of the fixation cross and largest number presented to the right of the fixation cross) and once in the descending order (i.e., smallest number presented to the right of the fixation cross and largest number presented to the left of the fixation cross); giving a total number of 36 items. The visual stimuli were presented by a computer positioned exactly in front of the participants and aligned with their body's midline. E-Prime (Psychology Software Tools, Pittsburgh, PA) was used to present the stimuli. Each

Table 1
List of stimuli used in the number bisection task.

	Distance		
Magnitude	5	7	9
Small	9–14	8–15	9–18
	8–13	9–16	8–17
Medium	29–34	18–25	18–27
	18–23	29–36	29–38
Large	59–64	68–75	68–77
	68–73	59–66	59–68

trial began with the presentation of a fixation cross (500 ms). Two numbers then appeared left and right of the fixation cross and stayed on the screen until participants gave a response. Reaction times were collected. There was no time limit but children received the instruction to judge and orally report the numerical midpoint of the number pair as quickly as possible, without calculating. Experimenter noted children's responses. The deviation score (DS) for each number pair was calculated as follows: participant's number midline estimation – true midline. As in the previous task, negative values indicated a left bias and positive values indicated a right bias. The absolute DS was also computed. Four practice trials were given before starting the experiment.

2.3.3. Number-to-position task

The number-to-position task was composed of 20 horizontal black lines 1 mm wide and 23 cm in length. Each line was labelled "0" at its left end and "100" at its right end. The lines were presented in the middle of four different white sheets of paper (21 cm × 30 cm – five lines per page). The sheet was laid in front of the participant's midline. Children were told that they had to show where they thought different numbers would fall on the line by marking the location with a pencil. Half the numbers to position were smaller than 50 (i.e., 4, 8, 13, 17, 22, 26, 31, 36, 41, 45); the other half were larger (i.e., 55, 59, 64, 69, 74, 78, 83, 87, 92, 96). These numbers were randomly presented and written at the left of each line. The experimenter covered each line after it was marked to ensure that the participants were not biased by their previous responses. There were no time restrictions. The deviations to the true number's position were carefully measured. The DS for each number was computed as follows: participant's number estimation – true number. Negative values indicated a left bias, positive values a right bias. The absolute DS was computed as well.

2.3.4. Simon task

In this task, participants were asked to judge whether a visually presented rectangle was either red or green. The stimuli were presented by a computer positioned exactly in front of the participants and aligned with their body's midline. The target rectangles appeared to the left or to the right of a fixation cross. Participants were instructed to respond as quickly and accurately as possible in a forced two-choice paradigm by pressing one of two response keys placed 20 cm in front of each participant's body and 10 cm away from the body midline in the left and right hemi-spaces. The task comprised two response assignments. In the first one, "green rectangle" was assigned to the left response key, while "red rectangle" was assigned to the right response key. In the second condition, the reverse assignment was used: the "red rectangle" was assigned to the left key and the "green rectangle" to the right key. To aid understanding of the instructions, response keys were coloured in green and red. Children were therefore told to press the response key which had the same colour as the rectangle presented. Children were moreover required to perform the task either with their hands in a parallel posture (i.e., uncrossed posture) or with their arms crossed over the body midline so that the left hand was on the right response key and the right hand was on the left response key (i.e., crossed posture). Each child completed four blocks of trials [response mode (2) × posture (2)]. Each block included 16 congruent trials (i.e., children had to press the response key which was on the same side as the target rectangle) and 16 incongruent trials (i.e., the target rectangle was not presented on the same side as the appropriate response key), giving a total number of 128 trials. The order of response mode and posture conditions was counterbalanced across participants. Stimuli were delivered and reaction times were recorded using E-Prime software (Psychology Software Tools, Pittsburgh, PA). Each trial began with the presentation of a fixation cross for 500 ms. A green or a red rectangle then appeared left or right of a fixation cross until participants gave a response. The inter-stimuli interval ranged from 800 to 1200 msec. Eight practice trials were given before beginning the task and eight other practice trials were given before changing hand posture.

2.3.5. Numerical comparison task

In this task, participants were asked to judge whether an Arabic digit was smaller or larger than 5. The Arabic digits used were numbers 1–9 (except for 5). Participants were instructed to respond as quickly and accurately as possible in a forced two-choice paradigm by pressing one of two response keys placed 20 cm in front of each participant's body and 20 cm away from the body midline in the left and right hemi-spaces. The task comprised two response assignments. In the first condition, the "smaller than 5" response was assigned to the left response key, while the "larger than 5" response was assigned to the right response key. In the second condition, the reverse assignment was used: the "larger than 5" response to the left key and the "smaller than 5" response to the right key. To aid understanding of the instructions, small and large snowmen were associated to the appropriate response key. Children were moreover asked to perform the task either with their hands in a parallel posture (i.e., uncrossed posture) or with their arms crossed over the body midline. Each participant completed 4 blocks of trials [response mode (2) × posture (2)]. The order of response mode and posture conditions was counterbalanced across participants. Stimuli were delivered and reaction times were recorded using E-Prime. Each Arabic digit was presented eight times in each condition, giving a total of 192 stimuli [number (8) × presentation (6) × response mode (2) × posture (2)] randomly presented in four experimental blocks. Each trial began with the presentation of a fixation cross for 500 ms. An Arabic number between 1 and 9 (except 5) then appeared in the centre of the computer screen and remained on the screen until participants responded. The inter-stimuli interval ranged from 800 to 1200 ms. Eight practice trials were given before starting the experiment and before changing the hand posture.

3. Results

3.1. Screening tasks

The Cornoldi shortened visuo-spatial questionnaire was not completed by the parents of 5 NVLD children. The vocabulary subtest was not completed by 2 NVLD children and the matrix reasoning subtest was not completed by 1 NVLD child. As shown in Table 2, both groups presented similar VIQ but differed in all the other screening tasks.

3.2. Experimental tasks

3.2.1. Line bisection task

The DS of each group was first compared with an independent samples *t*-test and results showed that both groups did not differ from each other, $t(28) = -1.53$, $p > .1$. Then, in order to examine whether children's responses were under- or over-estimated, the DS was submitted to a one-sample *t*-test with 0 as the reference value. The pseudo-neglect effect was significant ($M = -0.09 \pm 0.04$), $t(29) = -2.41$, $p < .05$, thus showing that children underestimated the true midline.

To investigate children's precision, a 2 (length: 8 cm vs. 16 cm) × 2 (group: control vs. NVLD) repeated measures ANOVA was performed on the absolute values of the DS (i.e., |DS|). Age of the participants was centred (i.e., age of the participant – mean age) and entered as a covariate. One control child presented outlier data (2 standard deviations from the mean of the group) and was therefore excluded from the analysis. The length effect was significant, $F(1, 26) = 34.11$, $p < .001$, $\eta^2 = .57$: children's accuracy was lower in the 16 cm-line condition ($M = 0.66 \pm 0.07$) than in the 8 cm-line condition ($M = 0.38 \pm 0.04$). There was no group effect, $F(1, 26) = 2.53$, $p > .1$, $\eta^2 = .09$, and no interaction.

3.2.2. Number bisection

Responses that were outside the numerical interval were excluded from the following analyses: 17% of the data in the NVLD group and 0.18% of the data in the control group, $\chi^2(1) = 1574.57$, $p < .001$. NVLD children committed as many out-of-the-interval errors in the ascending order (42%) than in the descending order (58%), $\chi^2(1) = 2.56$, $p > .1$.

The DS of each group was then compared. There was no difference between both groups, $t(28) = 0.25$, $p > .8$. A one-sample *t*-test (reference value = 0) also demonstrated the presence of the pseudo-neglect effect ($M = -0.59 \pm 0.19$), $t(29) = -3.09$, $p < .01$.

Then, to analyse the precision of children's responses, a 3 (magnitude: small, medium and large) × 3 (distance: 5, 7, and 9) × 2 (order: ascending vs. descending) repeated measures ANOVA was performed on the |DS|, with group as the between-subject factor and centred age as a covariate. Five NVLD children were excluded because they produced so many out-of-the-interval errors that some cells were missing in the ANOVA table. A distance effect was highlighted, $F(2, 44) = 32.39$, $p < .001$, $\eta^2 = .60$: larger the numerical interval presented, larger the errors committed (all *p*'s < .001). There was also a significant effect of group, $F(1, 22) = 7.43$, $p < .05$, $\eta^2 = .25$. NVLD children were less accurate ($M = 1.49 \pm 0.16$) than controls ($M = 0.94 \pm 0.13$). No other effects or interactions were significant.

Table 2
Scores in the screening tasks.

	NVLD	Control	*t*
Cornoldi	20.7 ± 4.87	34.67 ± 4.48	$t(23) = -7.37^{**}$
NEPSY	42.6 ± 12.59	59.87 ± 3.38	$t(28) = -5.13^{**}$
Rey	16.93 ± 2.74	33.33 ± 0.70	$t(28) = -5.79^{**}$
Block design	3.87 ± 2.42	13.07 ± 2.68	$t(28) = -9.86^{**}$
Matrix reasoning	6.64 ± 3.10	12.80 ± 2.14	$t(27) = -6.25^{**}$
Vocabulary	12.31 ± 3.82	14.13 ± 2.20	$t(26) = -1.83$
Similarity	14.13 ± 3.58	15.73 ± 1.98	$t(28) = -1.51$

** $p < .001$.

The same analysis performed on the logarithm of the median reaction times (RT; expressed in ms for the ease of comprehension) demonstrated: (1) a magnitude effect, $F(2, 44) = 10.32$, $p < .001$, $\eta^2 = .32$: small magnitudes ($M = 5695.95 \pm 465.15$) were responded faster than large magnitudes ($M = 6585.02 \pm 493.41$), $p = .001$; (2) a distance effect, $F(2, 44) = 9.12$, $p < .001$, $\eta^2 = .29$: reaction times for distance 9 ($M = 6591.86 \pm 528.80$) were longer than reaction times for distances 5 ($M = 5764.51 \pm 422.47$) and 7 ($M = 6102.47 \pm 511.04$), p's $< .05$; the difference between the distances 5 and 7 was marginally significant, $p = .07$; (3) a group effect, $F(1, 22) = 5.52$, $p < .05$, $\eta^2 = .20$: NVLD children ($M = 6989.68 \pm 732.86$) were slower than the controls ($M = 5316.22 \pm 598.38$), and (4) an order effect, $F(1, 22) = 10.50$, $p < .01$, $\eta^2 = .32$: children performed the ascending order ($M = 5974.49 \pm 480.28$) faster than the descending order ($M = 6331.41 \pm 479.92$). This order effect interacted with the group, $F(1, 22) = 5.01$, $p < .05$, $\eta^2 = .18$. In the NVLD group, there was no difference between the ascending ($M = 6980.06 \pm 947.27$) and descending order ($M = 6999.30 \pm 856.05$), $t(9) = -0.06$, $p > .9$. In the control group, RT were faster in the ascending order ($M = 4968.92 \pm 470.93$) than in the descending order ($M = 5663.51 \pm 539.78$), $t(14) = -4.07$, $p < .001$ (see Fig. 1).

3.2.3. Number-to-position

One NVLD child was not included in the analysis because he did not understand the instructions of the task. The children's DS were first submitted to an independent samples *t*-test which showed that both groups were not different from each other, $t(27) = -0.27$, $p > .7$. The pseudo-neglect effect was moreover significant ($M = -0.74 \pm 0.20$), $t(28) = -3.66$, $p = .001$, suggesting that children underestimated the correct answer.

A repeated measures ANOVA, with magnitude (small vs. large) as within-subject factor, group (NVLD vs. control) as between-subject factor and centred age as a covariate was carried on the $|DS|$. This analysis revealed a significant effect of group, $F(1, 26) = 11.11$, $p < .01$, $\eta^2 = .30$, and a significant effect of centred age, $F(1, 26) = 8.41$, $p < .01$, $\eta^2 = .24$. NVLD children committed larger errors ($M = 2.80 \pm 0.39$) than control children ($M = 1.09 \pm 0.38$). Performance also increased with age. No other effects were highlighted.

Additional analyses were conducted to compare the fit of linear and logarithmic models to the median estimates of the target numerical values. In the NVLD group, the logarithmic equation accounted for 84% of the variance, whereas the best-fitting linear equation accounted for 98%. In the control group, the logarithmic equation accounted for 83% of the variance, whereas the best-fitting linear equation accounted for 99%. In both groups, children's estimates therefore fit the linear model better than the logarithmic one (see Fig. 2).

3.2.4. Simon task

The order of posture conditions (crossed-first vs. uncrossed-first) had no effect on performance, $t(28) = -0.49$, $p > .6$ for the accuracy scores; $t(28) = 1.01$, $p > .3$ for the median RT. Both orders were therefore merged in the following analyses. To examine the accuracy scores (i.e., number of correct responses) more specifically, a Group (NVLD vs. Control) × Condition (congruent vs. incongruent) × Posture (crossed vs. uncrossed) repeated measures ANOVA was calculated on the number of correct responses, with centred age as a covariate. This only showed a main effect of posture ($M = 30.87 \pm 0.26$ out of 32 items in the uncrossed posture; $M = 30.17 \pm 0.40$ in the crossed position), $F(1, 27) = 8.77$, $p < .01$, $\eta^2 = .24$.

A similar analysis was performed on the logarithm of the median reaction times (RT; expressed in ms for the ease of comprehension) of the correct responses. Results demonstrated a main effect of posture, $F(1, 27) = 8.32$, $p < .01$, $\eta^2 = .24$, and a main effect of condition, $F(1, 27) = 14.69$, $p < .01$, $\eta^2 = .35$. Children responded faster in the uncrossed ($M = 696.82 \pm 61.89$) than in the crossed position ($M = 736.55 \pm 34.43$). Participants also responded faster when the location of the rectangle was congruent with the location of the response ($M = 704.80 \pm 46.10$) than when it was incongruent ($M = 728.57 \pm 44.14$). The group effect was not significant, $F(1, 27) = 2.81$, $p > .1$, $\eta^2 = .09$ ($M = 793.82 \pm 63.60$ and $M = 639.56 \pm 63.60$ for NVLD and control children, respectively) while RT decreased with age, $F(1, 27) = 12.14$, $p < .01$,

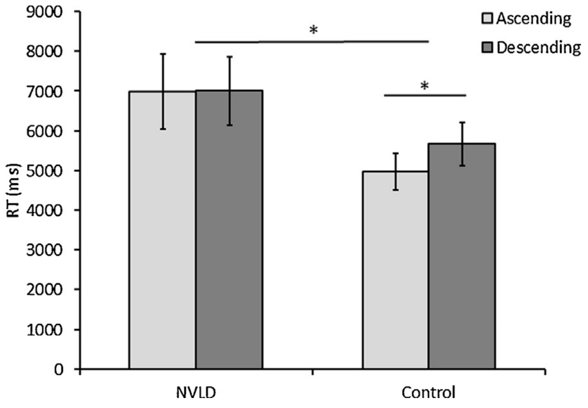

Fig. 1. Median RT in the number bisection task. Error bars denote standard error of the mean.

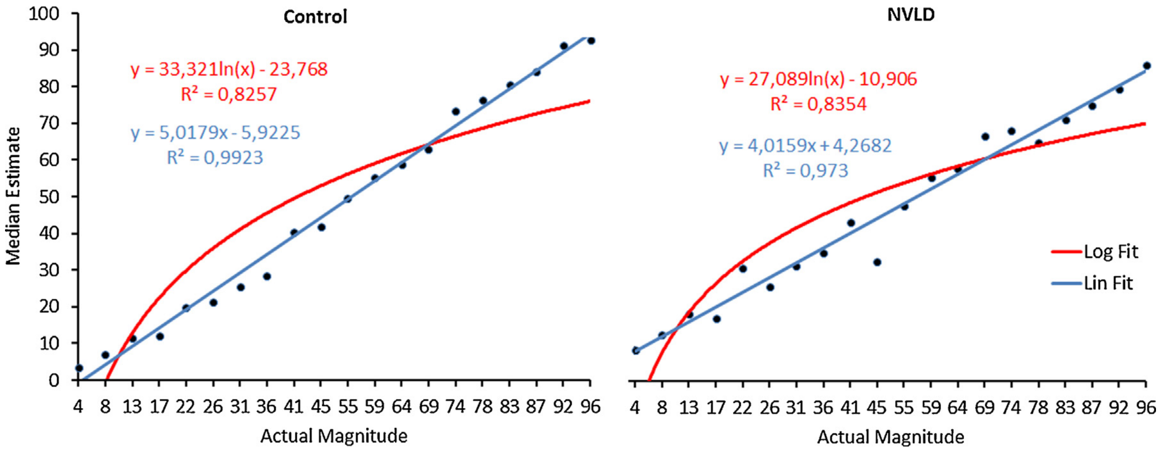

Fig. 2. Logarithmic and linear fitting of the number-to-position task in the control and NVLD groups.

$\eta^2 = .31$. No other effect or interaction was highlighted, suggesting that the Simon effect was present and similar in both groups and in both hands positions (see Fig. 3).

3.2.5. Numerical comparison task

A child from each group was removed from the analyses because both presented some outlier data, 2 standard deviations away from the mean of their group. The order of posture conditions (crossed-first vs. uncrossed-first) had no effect on performance, $t(26) = -1.11$, $p > .2$ for the accuracy scores; $t(26) = 0.35$, $p > .7$ for the median RT. Both orders were therefore merged in the following analyses.

In order to look at the precision of the mental number line, the distance effect was first examined using a repeated-measures ANOVA on the accuracy scores (i.e., number of correct responses). This ANOVA was run on the 4 levels of the distance towards the reference number five (i.e., distance 1, 2, 3 and 4), the posture (uncrossed vs. crossed) and the group (high vs. low). Centred age was entered as a covariate. Results showed the typical effect of distance, $F(3, 75) = 7.35$, $p < .001$, $\eta^2 = .23$, indicating that children were less accurate when the target number was close to the reference number five. A marginal effect of group was obtained, $F(1, 25) = 3.53$, $p = .07$, $\eta^2 = .12$: control children ($M = 23.09 \pm 0.41$ out of 24 items) tended to be more accurate than NVLD children ($M = 21.95 \pm 0.41$). The effect of centred age was also significant, $F(1, 25) = 7.19$, $p < .05$, $\eta^2 = .22$. Finally, results also highlighted a significant posture × group interaction, $F(1, 25) = 4.68$, $p < .05$, $\eta^2 = .16$. No difference between hands positions was observed in the control group, $t(13) = -0.74$, $p > .4$, while NVLD children were more accurate in the uncrossed position ($M = 22.30 \pm 0.47$) than in the crossed posture ($M = 21.59 \pm 0.68$), $t(13) = 2.16$, $p < .05$. In order to provide an estimate of effect size, empirical 95% confidence intervals for accuracy differences were also determined by bootstrap resampling producing ten thousand bootstrap samples with replacement for each group. The analysis was implemented in R (R Foundation for Statistical Computing, Vienna, Austria) (see Annex 1 for a detailed description of the code used). Both upper and lower bounds of the percentile bootstrap confidence interval were above zero ([0.15–2.34]) for the mean

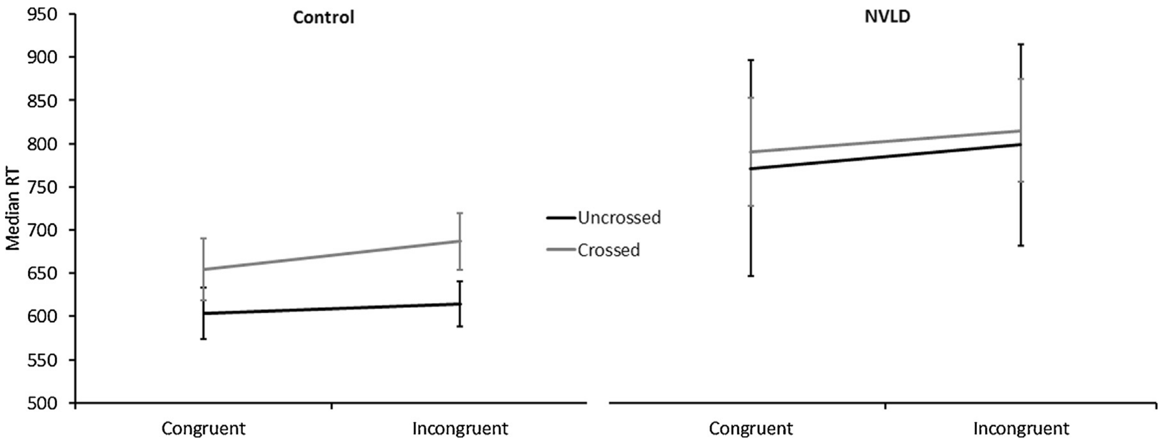

Fig. 3. Results of the Simon task. Error bars denote standard error of the mean.

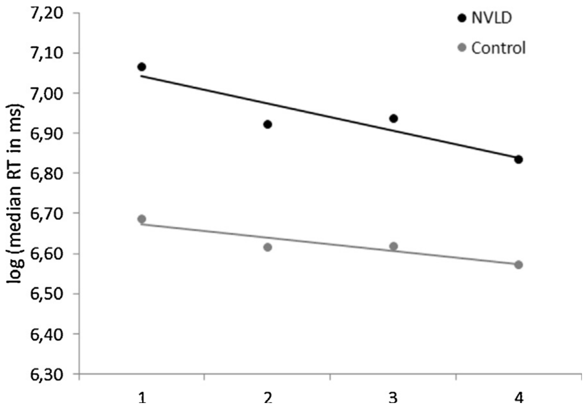

Fig. 4. Distance effect in the numerical comparison task.

accuracy measure, thus showing a positive group difference (i.e., the control group performed better than the NVLD group).[2] Zero was however comprised into the 95% percentile bootstrap confidence interval ([−0.50 to 2.13]) for the median accuracy measure. This result is probably due to the fact that the NVLD scores seem less symmetrically distributed than the scores of the control group. The presence of an individual lower score in the NVLD group could therefore have influenced the mean result downward while having less impact on the median result. Testing a larger sample of participants could be useful for a better description of the differences between groups.

Another repeated-measures ANOVA was then carried out on the logarithm of the median RT of the correct responses (expressed in ms in the paper). Results showed: (1) a main effect of distance, $F(3, 75) = 41.75$, $p < .001$, $\eta^2 = .62$: participants were slower when the target number was close to the reference number five; (2) a main effect of posture, $F(1, 25) = 7.31$, $p < .05$, $\eta^2 = .23$: participants responded faster in the uncrossed position ($M = 828.62 \pm 38.33$) than in the crossed posture ($M = 894.80 \pm 48.52$); (3) a main effect of group, $F(1, 25) = 12.44$, $p < .01$, $\eta^2 = .33$: reaction times were longer in the NVLD group ($M = 991.79 \pm 58.09$) than in the control group ($M = 731.62 \pm 58.09$); (4) an effect of centred age, $F(1, 25) = 13.03$, $p < .01$, $\eta^2 = .34$, suggesting that reaction times decreased with age; and (5) a distance × group interaction, $F(3, 75) = 6.24$, $p < .01$, $\eta^2 = .20$. In order to decompose this interaction, regression equations including reaction times as the dependent variable and distances as the independent variable were fitted for each participant separately (Lorch & Myers, 1990). The coefficients then obtained for each child in each group were compared and submitted to an independent samples *t*-test which revealed that the slope of the distance effect was larger in the NVLD group (ß = -75.70 ± 11.92) than in the control group (ß = -22.85 ± 4.15), $t(26) = -4.19$, $p < .001$ (see Fig. 4).

A last analysis was finally performed to measure the SNARC effect. For each child, the median RT of the correct responses was computed for each number and in each hand position. Because the SNARC effect predicts a negative relation between the magnitude of the number and the difference in RT between the right and the left-sided responses, dRT were computed by subtracting the median RT for the left response key from the median RT for the right response key (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). We then regressed dRT on number magnitude by means of a regression analysis (Lorch & Myers, 1990). If there is an association between the number magnitude and the side of the response (SNARC effect), a negative correlation between number magnitude and dRT should be observed: small numbers should elicit faster left responses (positive dRT) while large numbers should elicit faster right responses (negative dRT). In order to test this prediction, independent samples *t*-tests with a reference value of 0 were performed on the regression slopes of each hand posture and in both groups of children. While the control group demonstrated the SNARC effect in the uncrossed, $t(13) = -2.82$, $p < .05$, as well as in the crossed hand position, $t(13) = -2.34$, $p < .05$, no SNARC effect was observed in the NVLD group, $t(13) = -0.15$, $p > .8$ in the uncrossed posture; $t(13) = 1.45$, $p > .1$ in the crossed position (see Fig. 5). Both groups did however not differ in the uncrossed position, $t(26) = 0.59$, $p > .5$, while a significant group difference was highlighted in the crossed position, $t(26) = 2.07$, $p < .05$.

4. Discussion

In the literature on numerical cognition, it has been demonstrated that low visuo-spatial skills have a significant impact on mathematical activities (Szucs et al., 2013), especially those that require some space processing such as geometry or written calculation (Mammarella et al., 2010, 2013; Vaivre-Douret et al., 2011; Venneri et al., 2003). Given the strong association between space and number magnitude representation (see Hubbard, Piazza, Pinel, & Dehaene, 2005 for a review)

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[2] The effect of the group on the individual accuracy was also examined using a bootstrapped linear model controlling for the age (see Annex 1 for the description of the R code). It gets a similar conclusion: the 95% percentile bootstrap confidence interval doesn't contain zero as a value for the coefficient related to the group effect [0.11–1.94].

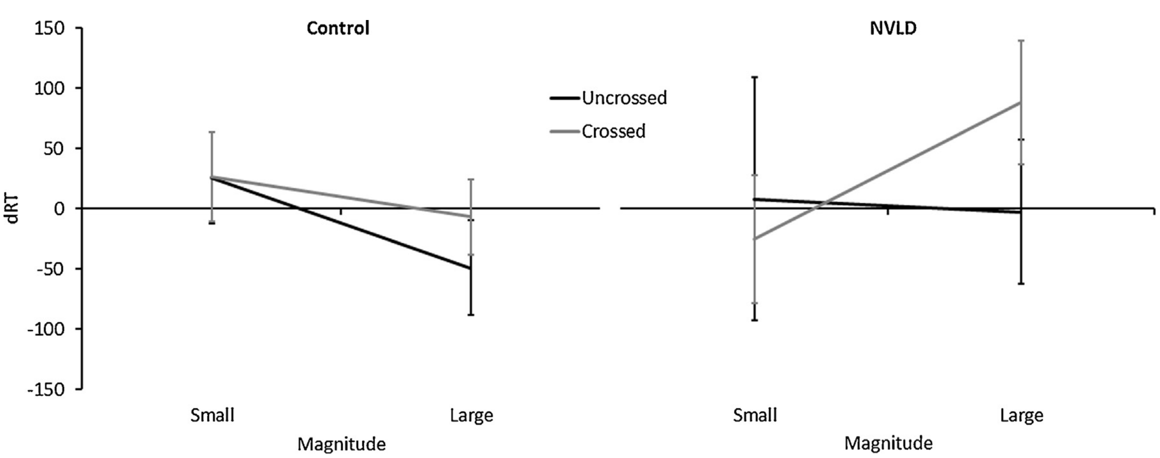

Fig. 5. Results of the numerical comparison task. Error bars denote standard error of the mean.

one may wonder whether visuo-spatial disabilities could also have an impact on the number magnitude representation itself. To our knowledge, only one study has been dedicated to explore this question (Bachot, Gevers, Fias, & Roeyers, 2005). In this experiment, the SNARC effect was investigated in a group of children presenting combined visuo-spatial and numerical disabilities. While the SNARC effect was significant in the control group, it was not present in the group of children with NVLD and dyscalculia. This absence of SNARC effect in this clinical group was interpreted as an indication that NVLD induces abnormality in representing numerical magnitudes on an oriented mental number line. However, as the children tested were selected as presenting both NVLD and math difficulties, the absence of SNARC effect could be linked to the math difficulties, to the NVLD or to the combined presence of both disabilities.

In order to further examine the spatial and numerical weaknesses of NVLD, the present study therefore submitted NVLD and control children to different spatial (the line bisection and Simon tasks) and numerical tasks (the number bisection, number-to-position and numerical comparison tasks). In this paper, NVLD children were selected on the basis of their visuo-spatial weaknesses only. We first investigated whether NVLD only affects pure spatial processing or whether it also affects basic numerical reasoning. Accuracy of both groups was measured but we also examined whether NVLD children presented the same pseudo-neglect, Simon and SNARC effects as their control peers. Overall, the control group outperformed the NVLD children in the number bisection and number-to-position tasks. Both groups of children did nevertheless not differ as far as the pseudo-neglect and the Simon effects are concerned.

The second aim of our study was to evaluate the impact of NVLD on number magnitude processing. Our data highlighted that NVLD affected the number-to-position task, i.e. a task that requires both the processing of a number magnitude and the mapping between this magnitude and a spatial medium. In this task, children with NVLD were less precise than control children. However, it is not easy to disentangle which dimension accounts for this lower precision: the spatial component of the task or the number magnitude processing. More importantly, differences between the two groups were also observed in the tasks that tagged number magnitude but did not involve a physical spatial medium (the number bisection and numerical comparison tasks). In the number bisection task, children with NVLD were less accurate and produced more aberrant responses than children in the control group. This difference also holds in the numerical comparison task, a 2-forced choice paradigm. In that task, children with NVLD were slower, tended to be less accurate than control children and also had a larger distance effect than control children. Altogether, this suggests that children with NVLD have a less precise numerical representation than their control peers. Furthermore in the number bisection task, NVLD children did not show any order effect. Their responses were indeed as fast in the descending order than in the ascending order. The NVLD children did therefore not seem to benefit from the congruency effect that occurs when the presentation order of the numerical interval is congruent with the spatial orientation of the mental number line.

Finally, as children were required to perform the Simon and the numerical comparison tasks with their hands in parallel or crossed over the body midline, we were also able to examine whether NVLD affects the development of the effector-independent frame of reference. At the spatial level, no difference was observed between both groups: control as well as NVLD children manifested the standard Simon effect in the uncrossed as well as in the crossed hands positions. The effector-independent coordinate system seems therefore to guide the spatial behaviour of both groups (Röder et al., 2007). While this coordinate system also guides the behaviour of the control children in the numerical comparison task, we were not able to draw firm conclusions for the NVLD group. As NVLD children did not demonstrate the SNARC effect, it was not possible to establish which frame of reference was the most salient in this population and in this specific task (Dehaene et al., 1993; Wood, Nuerk, & Willmes, 2006).

Globally, NVLD children presented a pattern of results which is quite comparable to the one Crollen and Noël (2015) observed in a group of children presenting low visuo-spatial abilities but no NVLD diagnosis. This is particularly true in the line bisection and Simon tasks. Some differences however appeared in the number bisection and number comparison tasks.

NVLD children first produced more out-of-interval responses than low visuo-spatial children in the number bisection task (respectively, 5.55% and 17% for the low visuo-spatial skills and the NVLD children). Furthermore and in contrast to low visuo-spatial children, the NVLD group was not affected by the presentation order of the numbers constituting the numerical interval to be processed. Second, a SNARC effect was observed in both uncrossed and crossed-hand positions in low visuo-spatial skills children whereas it is absent in NVLD children. The fact that reaction times of the NVLD group were not affected by the order effect in the number bisection task, together with the absence of SNARC effect in this group, suggests that NVLD might be related to peculiarities in the spatial coding of the number magnitude representation (as seen in Bachot et al., 2005). It is possible that NVLD actually leads to a disturbed spatial orientation of the mental number line or to a less salient left-to-right orientation of this representation. This absence of saliency is probably reduced in the number-to-position task as this task induces the use of anchors (the "0" label at the left end and the "100" label at the right end). In this last task, NVLD, low visuo-spatial (Crollen & Noël, 2015) and control children were shown to use a linear mapping rather than a logarithmic one. However, we have to acknowledge that we could have observed different results if a larger scale had been used (0–1000 rather than 0–100; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003). This idea remains to be tested.

The failure to find a SNARC effect in NVLD children could be interpreted according to 2 different hypotheses. As already mentioned in Section 1, the SNARC effect was first interpreted as resulting from the spatial compatibility that occurs between the left-to right orientation of the mental number line and the spatial location of the response (Dehaene et al., 1993; Fischer, 2003; Fischer, Castel, Dodd, & Pratt, 2003; Hubbard et al., 2005). According to this "*visuo-spatial coding account*" (Gevers et al., 2010), NVLD may therefore affect the left-to-right orientation of the mental number line. Yet, the SNARC effect also received a "*verbal-spatial coding account*" (Gevers et al., 2010): the dimensional overlap between number and response location could also be situated at a verbal categorical level, i.e. at a level of spatial representation that is not analogous to physical space but that is tightly linked to language (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Gevers et al., 2010; Proctor & Cho, 2006; Santens & Gevers, 2008). The idea that the visuo-spatial and verbal-spatial coding accounts can be engaged differently in different tasks has received direct empirical support. The SNARC effect was indeed shown to disappear under spatial load in magnitude comparison tasks (Herrera, Macizo, & Semenza, 2008; van Dijck, Gevers, & Fias, 2009) while it was shown to disappear under verbal load in parity judgement tasks (van Dijck et al., 2009). From these studies, the SNARC effect was therefore assumed to primarily originate from visuo-spatial associations in magnitude comparison tasks while it was assumed to primarily arise from verbal associations in parity judgement tasks. As the task used in this paper was a numerical comparison task and as NVLD is characterized by intact verbal abilities but impaired visuo-spatial abilities (Mammarella & Cornoldi, 2014; Nichelli & Venneri, 1995; Rourke, 1989), it is tempting to assume that NVLD actually decreases the saliency of the left-to-right orientation of the mental number line. It could however be really interesting to examine whether NVLD might also affect the verbal coding of numerical space by submitting NVLD children to a parity judgement task.

To conclude, our paper showed that NVLD affected numerical processing. In particular, we showed that NVLD affected the accuracy of the mental number line as well as the saliency of its left-to-right orientation. The often reported math difficulties in NVLD would thus not solely appear in numerical tasks that involve an external spatial component (such as geometry and written calculation in columns or number-to-position on a line) but would also affect the number magnitude representation itself as it is supposed to be mentally coded on a spatial medium. While this paper highlighted basic numerical difficulties in NVLD, it does not give insights into the origins of these troubles. Some authors already proposed that NVLD's arithmetic difficulties could derive from a visuo-spatial working memory deficit (Mammarella et al., 2010; Venneri et al., 2003). In typically-developing children, spatial immediate memory capacity seems to increase throughout the early and middle school years to adolescence (Farrell Pagulayan, Busch, Medina, Bartok, & Krikorian, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004). Future research should therefore examine whether the atypical development of visuo-spatial working memory in NVLD could explain the pattern of failures that we observed in basic numerical tasks.

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Annex I

```
dta=read.csv2(“C:/Users/pollaris/Desktop/Consultation Stat/V Crollen – 19-06-2015/analyses27-7-2015/SNARC_Données_OK_Effet_dist_ACC.csv”, header=TRUE)
n=dim(dta)[1]
mean_id=apply(dta[,6:13], 1, mean) #A mean accuracy score computed by subject
group01=dta$Group-1 #This binary variable indicates 0=NVLD and 1=Control group
dta=cbind(dta,group01,mean_id)
dtaG1=dta[dta$Group==1,]
```

```
dtaG2=dta[dta$Group==2,]
n1=dim(dtaG1)[1]
n2=dim(dtaG2)[1]
Ybar1=mean(dtaG1$mean_id)
Ybar2=mean(dtaG2$mean_id)
Between_Subjects_Effects_Results=summary(lm(dta$mean_id~dta$group01+dta$Age))
B=10000
results_bootstrap=matrix(NA,nrow=B,ncol=8)
dimnames(results_bootstrap)=list(NULL,c(“YbootG1_bar”, “YbootG2_bar”, “diff_means_boot”, “YbootG1_median”,“Y-
bootG2_median”,“diff_medians_boot”,“reg_coeff_group”,“reg_coeff_age”))
for (i in 1:B) {
indexG1=sample(n1,size=n1,replace=TRUE)
indexG2=sample(n2,size=n2,replace=TRUE)
dta_bootG1=dtaG1[indexG1,]
dta_bootG2=dtaG2[indexG2,]
#means:
YbootG1_bar=mean(dta_bootG1$mean_id)
YbootG2_bar=mean(dta_bootG2$mean_id)
diff_means_boot=YbootG2_bar-YbootG1_bar
#medians:
YbootG1_median=median(dta_bootG1$mean_id)
YbootG2_median=median(dta_bootG2$mean_id)
diff_medians_boot=YbootG2_median-YbootG1_median
#Linear Model: the accuracy score as a function of the age and the group
dta_bootG1G2=rbind(dta_bootG1,dta_bootG2)
LM_result_boot=summary(lm(dta_bootG1G2$mean_id~dta_bootG1G2$group01+dta_bootG1G2$Age))
results_bootstrap[i,]=c(YbootG1_
bar,YbootG2_bar,diff_means_boot,YbootG1_median,YbootG2_median,diff_medians_boot,LM_result_boot$coef[2:3,1])
}
median(results_bootstrap[,“diff_means_boot”])
quantile(results_bootstrap[,“YbootG1_bar”],probs=c(0.025,0.975))
quantile(results_bootstrap[,“YbootG2_bar”],probs=c(0.025,0.975))
quantile(results_bootstrap[,“diff_means_boot”],probs=c(0.025,0.975))
median(results_bootstrap[,“diff_medians_boot”])
quantile(results_bootstrap[,“YbootG1_median”],probs=c(0.025,0.975))
quantile(results_bootstrap[,“YbootG2_median”],probs=c(0.025,0.975))
quantile(results_bootstrap[,“diff_medians_boot”],probs=c(0.025,0.975))
#Group effect: Age is controlled:
quantile(results_bootstrap[,“reg_coeff_group”],probs=c(0.025,0.975))
#Plot of observed data:
plot(dta$Group,dta$mean_id)
```

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