

Arabic digit processing in adults with Mathematical Learning Disability

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Arabic digit processing in adults with mathematical learning disability

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Samuel Lepoittevin: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. Gaétane Keymolen: Conceptualization, Methodology, Investigation. Michael Andres: Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition. Alice De Visscher: Conceptualization, Methodology, Formal Analysis, Writing - original draft, Visualization, Supervision, Project administration, Funding acquisition.

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Peer Review Version

Abstract

The processing of Arabic digits is a core difficulty of children suffering from mathematical learning disability (MLD). Dominant accounts assume a semantic impairment affecting either the magnitude representation *per se* or its access from numerical symbols. But recent data have raised the hypothesis that the impaired processing of Arabic digits may be explained by a selective deficit of digit visual recognition (i.e., recognizing a symbol as one of the digits, no matter its identity or numerical meaning). This study aims at testing whether the difficulty to process Arabic digits remains prevalent in adults with MLD and whether it is effectively associated with a digit visual recognition deficit. To do so, we compared 19 adults with MLD to 19 matched controls in an *Arabic digit comparison* task that required to identify the largest of two digits, and in an *Arabic digit lexical decision* task that required to decide whether a visual stimulus is a digit or not. The results showed that MLD participants took more time than control participants to perform the comparison task. In contrast, their performance in the digit lexical decision task was within the range of the control participants. Overall, this finding indicates that adults with MLD continue to experience difficulties to process the magnitude of Arabic digits efficiently, and this cannot be explained by a visual recognition deficit for Arabic digits. We conclude that their difficulties are best explained by an impaired representation of number magnitude or by an impaired access to this representation.

Keywords: Dyscalculia, Symbolic number comparison, Lexical decision, Visual recognition

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Mathematical learning disability (MLD) is a specific, severe and persistent disorder of numerical development and mathematical learning (American Psychiatric Association, 2013), which affects from 3% to 6% of the population (e.g., Shalev et al., 2000), depending on the inclusion threshold used, the testing instruments, and the numerical domains covered by the testing (e.g., arithmetical skills, mathematical conceptual knowledge). Most researchers agree that MLD is a heterogeneous disorder and different skills may be affected (Geary, 2004), such as reciting the number sequence (Landerl et al., 2004), transcoding from a symbolic code to another (Sullivan, 1996; Temple, 1989), learning and retrieving arithmetic facts (De Visscher & Noël, 2013; Geary et al., 2000), or using mature calculation strategies (Geary et al., 2000).

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A common observation among studies is that children with MLD seem to experience difficulties whenever they have to process numerical symbols (Schwenk et al., 2017), even in basic tasks such as magnitude comparison (see De Smedt et al., 2013, for a review). It is unclear whether these difficulties persist after schooling but a few observations suggest they still influence the digit comparison skills of adults with MLD (Wilson et al., 2015). This has prompted the hypothesis that inefficient processing of numerical symbols is a core feature of MLD. However, the nature of the underlying deficit is debated. According to the dominant account, this would be the expression of a general impairment affecting the approximate numerical system (ANS; Wilson & Dehaene, 2007), which is defined as an innate and phylogenetically inherited magnitude processing system whose precision is crucial for mathematical development because this system would provide a common ground for symbolic and non-symbolic number skills (Mazzocco et al., 2011a; Booth & Siegler, 2008). Supporting evidence comes from the finding that the precision of the ANS, as indexed by the discrimination ratio between two numerosities (e.g., dot collections), is lower in children with MLD than in age-matched control children (Mazzocco et al., 2011b; Piazza et al., 2010). Discrepant results come from studies reporting serious difficulties in Arabic digit comparison in a context of normal performance in dot collection comparison. The finding of disproportionate difficulties with symbolic vs. non-symbolic magnitude comparison does not match the role assigned to the ANS in MLD (De Smedt & Gilmore, 2011; Iuculano et al., 2008; Landerl & Kölle, 2009; Rousselle & Noël, 2007). Alternative accounts imply a selective deficit in the processing

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4 of symbolic numbers. One of these alternative accounts builds on models of numerical cognition where
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6 symbolic number representations (i.e., Arabic digits, number words) converge to a core representation
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8 of magnitude (Dehaene, 1992; McCloskey et al., 1985). Rather than the representation of numerical
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10 magnitude *per se*, it would be the access to this representation from symbols that is impaired, hence
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12 disrupting the matching of Arabic digits with their respective magnitude (Rousselle & Noël, 2007).
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14 Another alternative account considers that symbolic and non-symbolic comparisons rely on distinct
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16 representations that could be selectively impaired in MLD. Some behavioural (e.g., Marinova et al.,
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18 2021) and neurophysiological data (e.g., Roggeman et al., 2007) support the existence of distinct
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20 representations for numerosity (i.e., dots) and numerals (i.e., digits). Under this view, the acquisition of
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22 the symbolic code would lead to the elaboration of an exact representation that links the position of
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24 numbers in the verbal sequence to the cardinality they represent (Carey, 2001, 2009; Reynvoet &
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26 Sasanguie, 2016). Throughout development, this exact representation would map onto the approximate
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28 representation inherited from evolution to estimate numerosity, leading to its refining (Piazza et al.,
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30 2013). The main difference with the ANS theory is that the interaction between non-symbolic and
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32 symbolic numbers goes in the opposite direction. The refinement hypothesis is supported by empirical
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34 data showing that MLD is characterized by early difficulties in the processing of Arabic digits (i.e.,
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36 before the age of ten), followed later on by difficulties signaling a departure of the non-symbolic number
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38 system from the normal developmental trajectory (Noël & Rousselle; 2011).
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42 In contrast with these semantic accounts lies the possibility that children with MLD have
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44 difficulties to process Arabic digits efficiently because they take more time to visually recognize digits.
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46 We define the visual recognition of digits as the ability to match a percept as one of the Arabic digits,
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48 no matter its identity or meaning. Previous studies have shown that the slow performance of children
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50 with MLD in digit magnitude comparison is not due to low-level visual processes such as those
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52 underlying physical size comparison (Landerl & Kölle, 2009; Landerl, 2013). But the question of
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54 whether difficulties in magnitude comparison could arise from a pre-semantic deficit remains an open
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56 question. The best way to characterize this pre-semantic stage of digit processing is to refer to the
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58 allograph representation proposed by McCloskey and Schubert (2014). This representation finds a
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4 counterpart in numerical cognition models under the visual Arabic representation that has been
5 distinguished from the verbal and analogical representation (Dehaene, 1992; Dehaene & Cohen, 1995;
6 Pesenti et al., 2000). This processing stage is typically assessed through digit lexical decision tasks
7 (McCloskey & Schubert, 2014), which consist in deciding whether a symbol (digit or pseudo-digit) is a
8 digit or not, irrespective of its identity (and thus without requiring any semantical or transcoding
9 processing). A recent study showed that 8-9-year-old children with MLD committed more errors in this
10 simple digit lexical decision task than age-matched control children, suggesting an impairment of digit
11 recognition ability (Lafay et al., 2018). However, firm conclusions are prevented by the heterogeneity
12 of the groups and by the methodology used to assess digit recognition at a pre-semantic level. Indeed,
13 the group difference disappeared when standard measures of linguistic and non-verbal reasoning skills
14 were introduced as covariates. Moreover, their digit lexical decision task involved other characters as
15 distractors (letters and arithmetical signs). The performance thus reflects the ability to discriminate digits
16 from other characters, which corresponds to a subsequent processing that deals with the character
17 category and that is independent from its identification (McCloskey & Schubert, 2014). Therefore, it
18 remains unclear whether the difficulties that characterize the processing of Arabic digits in MLD can be
19 assigned to a visual recognition deficit. Finally, we have underlined the need to complement research
20 on MLD with data from adults in order to get a better idea of the pervasive nature of this disorder.
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40 The present study aims to fill this gap through an investigation of Arabic digit processing in
41 adults with MLD. The study includes magnitude comparison and digit lexical decision tasks to
42 distinguish between semantic and pre-semantic stages of processing, respectively. The Arabic digit
43 lexical decision task required participants to decide whether a sign was a digit or not, and pseudo-digits
44 – rather than other symbols – were used as distractors to avoid the involvement of categorical processing.
45 To further assess the integrity of symbol recognition, we also tested participants in a letter lexical
46 decision task where they had to decide whether the sign was a letter or not. We predict that (1) adults
47 with MLD should experience difficulties in the Arabic digit comparison task given that the symptoms
48 of MLD tend to persist over time (Wilson et al., 2015), and that (2) these difficulties should be
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3 accompanied by a poor performance in the digit lexical decision task if they originated from a pre-
4 semantic deficit.
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10 **Method**

13 **Participants**

16 Participants were native French-speaking adults, who gave their written consent. A convenience
17 sample was recruited through on-campus advertisements. They all met the two following inclusion
18 criteria: (1) being aged between 18 and 40 years; (2) being exempt from history of neurological or
19 psychiatric disease, and (3) their standard scores in the “Similitudes” (verbal reasoning skills) and
20 “Symboles” (processing speed) subtests of the French edition of the WAIS-IV battery (Wechsler, 2011)
21 could not be equal or inferior to the mean of the normative sample minus 2 SD (or superior to the mean
22 + 2 SD). Participants with MLD were included if they reported long-lasting mathematical difficulties,
23 which appeared during the first two years of primary school and had persisted since then, and if they
24 performed below the normative mean (Z -score < -1.5) on at least one of the measures provided by the
25 Arithmetic Battery (speed and accuracy; Shalev et al., 2001, modified by Rubinsten & Henik, 2005) and
26 the TempoTest Automatiseren (TTA; de Vos, 2010). Thirty-one adults volunteered, but 11 did not meet
27 the selection criteria (4 obtained a score inferior or equal to the mean of the normative sample minus 2
28 SD in the WAIS-IV subtests and 7 did not meet the severity criterion in the arithmetic tests). One of
29 them (MLD12) had to be excluded from the subsequent analyses because his median reaction time in
30 one of the computerized control tasks was identified as an outlier observation that compromised the
31 normal distribution of the data. Among the remaining participants, five showed impairment in the
32 Arithmetic Battery only, two in the TTA only, and 12 both in the Arithmetic Battery and TTA. The
33 control group (CG) included adults matched with the MLD participants in terms of age, gender,
34 lateralization, and educational level (number of completed school years). They were selected if they
35 obtained standard scores within the range defined by the mean of the normative sample ± 2 SD in the
36 subtests of the WAIS-IV battery and if they had no history of mathematical learning difficulty, as further
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4 evidenced by Z -scores ≥ -1 for all arithmetic measures. Nine volunteers did not meet the inclusion
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6 criteria regarding arithmetic performance and were replaced by other participants. The control
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8 participant matched with the outlier participant from the MLD group (CG12) was excluded from
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10 subsequent analysis as well, to obtain two groups of 19 participants with comparable socio-demographic
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12 profiles and equal non-verbal reasoning skills (see Table 1).
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18 19 20 21 **Task and Procedure**

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23 The study was approved by the ethical committee of the Psychological Sciences Research
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25 Institute of UCLouvain (Belgium). Experimental tasks were programmed using PsychoPy3 (Version
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27 3.1.5; Pierce, 2019) and run on a laptop computer with a 15.6-inch screen (1920 x 1080 resolution; 60
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29 Hz refresh rate). The screen was positioned 60 cm from the participants eyes, so that the relative size of
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31 the displayed stimuli allowed their apprehension by the fovea ($< 1^\circ$ from central position). Stimuli were
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33 images with a grey background, sharing the same resolution and original size. Before each task, written
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35 instructions were displayed on screen. Participants were asked to answer by pressing the left or right
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37 response key corresponding to the key "S" or "L" on the keyboard. The instructions emphasized both
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39 speed and accuracy. In each trial, the stimulus was preceded by a 500 ms fixation cross and remained
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41 on screen until the participant's response. The inter-trial-intervals were set to 500 ms. After collecting
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43 socio-demographic data, screening the participants for their arithmetic, processing speed and non-verbal
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45 reasoning skills, we administered the experimental tasks in the following order, for a total duration of
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47 120 minutes, including short breaks in-between the tasks.
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51 **Arabic digit comparison task.** The first experimental task was a computerized Arabic digit
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53 comparison task (COMPARISON). Stimuli consisted in the 72 possible pairs of digits, presented twice, for
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55 a total of 144 trials per subject. They remained on screen until response. Participants had to respond, as
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57 quickly as possible, by pressing the response key on the side of the digit with the largest numerical
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59 magnitude (see Figure 1A). The side of the correct response was counterbalanced across trials. The trial
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4 order was pseudo-randomized, so that participants did not respond more than 3 times in a row with the
5 same key, and the same stimulus did not appear 2 times in a row. The task started with a practice session
6 of 8 trials.
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10 **Lexical decision task on Arabic digits.** In the computerized digit lexical decision task (DIGIT-
11 DECISION), participants had to decide whether a given stimulus was a digit or not. The digits (Calibri)
12 ranged from 1 to 9, excluding 8 (see Figure 1B). Three sets of pseudo-digits were created by modifying
13 the spatial arrangement of the features constitutive of each digit, while avoiding discontinuity or overlap,
14 to end up with the same physical characteristics as the original digits (i.e., number of salient features,
15 density). To make the task more sensitive to interindividual differences, we increased the task difficulty
16 by adding a noisy background in half of the trials (0.5° noise filter available from the Psychopy
17 component library). Stimuli remained on screen until response. Participants had to respond as fast as
18 possible. Half of the MLD participants - and of the matched controls - responded to the digits with the
19 left key and to the pseudo-digits with the right key, whereas the other half of the participants received
20 the opposite response key assignment. The task counted 48 trials with a transparent background and 48
21 with a noisy background so that each digit was repeated three times and each pseudo-digit once in each
22 condition. The trial order was pseudo-randomized, so that participants did not see the same digit and/or
23 the same background three times in a row and that they did not respond more than three times in a row
24 with the same key. The task started with a practice session of 8 trials.
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43 **Lexical decision task on letters.** As a control condition, we designed another lexical decision
44 task that required participants to decide whether a given stimulus was a letter or not (LETTER-DECISION).
45 The task was identical in all aspects to the DIGIT-DECISION task, except that the stimuli (lower case,
46 Calibri) consisted in letters (a, e, f, h, k, r, s, t) and pseudo-letters created using the same method as for
47 pseudo-digits.
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53 **Choice reaction time tasks.** The COMPARISON and DIGIT-DECISION tasks were each
54 supplemented with a matched choice reaction time task (respectively CRT-COMP and CRT-DEC) designed
55 to account for the inter-individual variability in response speed resulting from domain-general processes
56 such as perception, attention or motor preparation (see Figure 1). In the CRT-COMP task, the stimuli
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4 consisted in pairs of red and blue rectangles, displayed side by side, as the digit pairs in the COMPARISON
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6 task. This task required participants to press the response key on the side of the red rectangle. In the
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8 CRT-DEC task, a red or blue rectangle was displayed alone at the center of the screen as the single
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10 characters presented in the lexical decision tasks. Participants were asked to decide whether the rectangle
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12 was red or not by pressing the correct response key. The two CRT tasks started with 4 practice trials
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14 followed by 30 test trials.
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17 --- Insert Figure 1 about here ---
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20 **Data Analysis**

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23 The median reaction times on correct trials (RTs) were calculated for each participant and each
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25 combination of task and condition. Errors were not analyzed because the mean accuracy ranged from
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27 96 to 99% across tasks (see Table 2). The RT data were log-transformed to obtain a normal distribution
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29 in each task and condition. The normal distribution was tested using Shapiro-Wilk (all $ps > .05$ after
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31 transformation) and, when relevant, the homogeneity of variances was verified and the residuals were
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33 analyzed to exclude any other abnormality in the distribution of the data. The untransformed RT data
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35 are reported in Table 2 and can be visualized on Figures 2, 4 and 5. Internal reliability was assessed for
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37 all experimental tasks using a split-half method with trials randomly assigned to one of the two halves.
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39 Spearman-Brown coefficients indicated excellent reliability for all tasks (CRT-COMP: .86; CRT-DEC: .86;
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41 COMPARISON: .98; DIGIT-DECISION: .92; LETTER-DECISION: .89). In order to investigate group
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43 differences, we conducted a 2x2 ANOVA on the $\text{Log}_{10}(\text{RT})$ with Task (COMPARISON or DECISION vs.
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45 CRT-COMP or CRT-DEC) as within-subjects factor and Group (MLD vs. CG) as between-subjects factor.
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47 Bonferroni correction was applied in post-hoc analyses. This frequentist approach was supplemented by
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49 Bayesian hypothesis testing using the Bayes Factor (BF_{10}), which is obtained by dividing the marginal
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51 likelihood of the alternative hypothesis by that of the null hypothesis (JASP Team, 2022). BF_{10} can vary
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53 between 0 and ∞ , where values below 1 provide increasing evidence in favour of the null hypothesis
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55 and values above 1 increasing evidence for the alternative hypothesis. Models receiving most supports
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57 from the data were then compared on the basis of the ratio of their BF_{10} (Wagenmakers et al., 2018).
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The group analyses were complemented with individual data analyses. We first regressed the RTs of the CG participants in the COMPARISON task as a function of their RTs in the matched control task (CRT-COMP). We then computed a 95% confidence interval around the regression line and identified the MLD participants whose RTs fell outside this interval on an XY graph. We also computed the differences in reaction time (dRTs) between the DIGIT-DECISION and CRT-DEC tasks and ranged them from the lowest to the highest to examine whether MLD participants - and more specifically those who were the most severely impaired in Arabic digit comparison - were outside the range of the control participants. Finally, to further explore the selectivity of difficulties in visual recognition, we directly compared digits and letters considering the influence of the background noise. The $\text{Log}_{10}(\text{RT})$ of both lexical decision tasks were entered in a 2x2x2 ANOVA with lexical decision Task (digits vs. letters) and Background (transparent vs. noisy) as within-subjects factors and Group (MLD vs. CG) as between-subjects factor.

--- Insert Table 2 about here ---

Results

Comparison of Arabic digits

The ANOVA revealed a main effect of Task ($F(1,36) = 235.15, p < .001, \eta^2_p = .867$), with faster RTs in the CRT-COMP task ($M = 366$ ms, $SD = 35$ ms) than in the COMPARISON task ($M = 506$ ms, $SD = 100$ ms), and a main effect of Group ($F(1,36) = 30.26, p < .001, \eta^2_p = .457$), with faster RTs in CG ($M = 395$ ms, $SD = 60$ ms) than in MLD participants ($M = 477$ ms, $SD = 119$ ms). The analysis also revealed a significant Group by Task interaction ($F(1,36) = 21.29, p < .001, \eta^2_p = .372$). Post-hoc comparisons showed that CG answered faster than MLD in either task (CRT-COMP: $t(36) = 2.78, p = .027$; COMPARISON: $t(36) = 5.94, p < .001$). However, the difference in RTs between the two tasks was larger in the MLD ($M = 193$ ms, $SD = 87$ ms) than in the CG ($M = 87$ ms, $SD = 39$ ms; $t(36) = 5.69, p < .001$), pointing to specific difficulties in Arabic digit magnitude comparison (see Figure 2). In order to take into account the group difference observed on the WAIS-IV Symbolics, we replicated the analysis while introducing the unstandardized scores on this subtest as a covariate. The results were strictly similar, in

particular the Group by Task interaction remained significant ($F(1,35) = 15.68, p < .001, \eta^2_p = .309$). The Bayesian ANOVA shows that the data best support a model including the main effect of Group, the main effect of Task, and their interaction as predictors ($BF_{10} = 1.162e+20$). Adding the Group by Task interaction increases the degree of support by a factor of 435 compared to a model that would only include the main effects of Group and Task ($BF_{10} = 2.672e+17$). This indicates that the Group by Task interaction receives overwhelming support from the data (Wetzels et al., 2015).

--- Insert Figure 2 about here ---

The analysis of individual data indicated that 7 out of 19 MLD participants were slower in the COMPARISON task than what could be expected from their RTs in the matched choice reaction time task. As illustrated in Figure 3, the RTs of these MLD participants are out of the 95% confidence interval along the regression line describing the performance of the CG participants ($\text{COMPARISON } \text{Log}_{10}(\text{RT}) = -0.2 + 11.1 * \text{CRT-COMP } \text{Log}_{10}(\text{RT}), t = 4.093, p < .001$).

--- Insert Figure 3 about here ---

Visual recognition of Arabic digits

The ANOVA, with Task (DIGIT-DECISION vs. CRT-DEC) as within-subjects factor and Group (MLD vs. CG) as between-subjects factor, revealed a main effect of Task ($F(1,36) = 276.53, p < .001, \eta^2_p = .885$), with faster RTs in the CRT-DEC task ($M = 412 \text{ ms}, SD = 44 \text{ ms}$) than in the DIGIT-DECISION task ($M = 578 \text{ ms}, SD = 70 \text{ ms}$). We also found a main effect of Group ($F(1,36) = 16.44, p < .001, \eta^2_p = .313$), indicating that CG participants ($M = 469 \text{ ms}, SD = 100 \text{ ms}$) responded faster than MLD participants ($M = 520 \text{ ms}, SD = 98 \text{ ms}$). However, there was no significant interaction between Group and Task ($F(1,36) = .06, p = .813$), meaning that the slower performance of MLD was not specific to the digit lexical decision task (see Figure 4). Similar results were observed after introducing the unstandardized score on the WAIS-IV Symboles as a covariate, in particular no interaction was found

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4 between Group and Task ($F(1,35) = .86, p = .359$). The Bayesian ANOVA shows that the data best
5 support a model including the main effects of Group and Task as unique predictors ($BF_{10} = 4.714e+22$).
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7 The model including the Group by Task interaction receives less support from the data ($BF_{10} =$
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9 $1.541e+22$). Actually, adding the Group by Task interaction to the model including only the main effects
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11 as predictors decreases the degree of support by a factor of 3.
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18 In order to test the hypothesis that a weak performance in digit visual recognition could account
19 for difficulties in magnitude processing at least in those who are the most affected, we examined the
20 distribution of the dRTs in the COMPARISON task (Figure 5A) and in the DIGIT-DECISION task (Figure
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22 5B). A quick look at the two graphs shows that the MLD participants that were the most impaired in the
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24 COMPARISON task (in red) fall within the range of the control participants in the DIGIT-DECISION task:
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26 several CG participants actually responded slower than these MLD participants after baseline correction.
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28 Thus, the dissociation between impaired digit comparison and preserved digit recognition also holds at
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30 the individual level.
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34 Note that one control participant (CG19) was markedly slower than the rest of the sample in the
35 DIGIT-DECISION task on Figure 5B. To exclude that this outlier performance could have biased the group
36 comparison, we replicated the analyses after filtering out this participant and the matched MLD
37 participant. The results were strictly similar to what had been observed in the previous analyses,
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39 revealing a main effect of Task ($F(1,34) = 357.26, p < .001, \eta_p^2 = .913$) and Group ($F(1,34) = 15.76, p$
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41 $< .001, \eta_p^2 = .317$) but no significant interaction between Group and Task ($F(1,34) = .29, p = .593$).
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52 In order to assess the influence of the background noise, we conducted another ANOVA with
53 lexical decision Task (digits vs. letters) and Background (transparent vs. noisy) as within-subjects
54 factors and Group (MLD vs. CG) as between-subjects factor. The results revealed a main effect of
55 Background ($F(1,36) = 310.06, p < .001, \eta_p^2 = .896$), with faster RTs in the transparent ($M = 544$ ms,
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57 $SD = 68$ ms) than in the noisy condition ($M = 616$ ms, $SD = 75$ ms). There was no effect of the Task
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($F(1,36) = .28, p = .603$), but a significant interaction between Task and Background ($F(1,36) = 4.21, p = .047, \eta^2_p = .105$). Post-hoc comparisons showed that transparent stimuli are answered faster than noisy ones in both lexical decision tasks (DIGIT-DECISION: $t(37) = -12.72, p < .001$; LETTER-DECISION: $t(37) = 17.16, p < .001$). However, the difference in RT between the two backgrounds was larger in the LETTER-DECISION ($M = 78$ ms, $SD = 33$ ms) than in the DIGIT-DECISION ($M = 66$ ms, $SD = 33$ ms; $t(37) = -2.54, p = .048$). Finally, we found a main effect of Group ($F(1,36) = 11.17, p = .002, \eta^2_p = .237$), indicating that CG participants ($M = 548$ ms, $SD = 75$ ms) responded faster than MLD participants ($M = 612$ ms, $SD = 72$ ms), but this factor did not interact with Task and/or Background factors (i.e., all p -values $> .121$). The Bayesian ANOVA shows that the data best support a model including the main effects of Background and Group as unique predictors ($BF_{10} = 4.505e+28$). A model including the Task by Group interaction receives less support from the data ($BF_{10} = 1.409e+28$), as well as a model including the triple interaction between Task, Background and Group ($BF_{10} = 5.308e+26$).

Discussion

The results show that, when they have to compare the magnitude of Arabic digits, adults with MLD take more time than typically developed people, and this increase in response latency cannot be explained by attention-, decision- or response-related processes that were carefully controlled in a matched choice reaction time task used as a baseline. A fine-grained analysis of individual data indicated that 7 out of the 19 participants with MLD exhibited a larger slowdown in the Arabic digit comparison task than what could be expected from their response latency in the matched choice reaction time task. The main implication is that the difficulties experienced by children with MLD maintain over development until adulthood (De Smedt & Gilmore, 2011; Landerl & Kölle, 2009; Rousselle & Noël, 2007; Wilson et al., 2015). Hence, adults with MLD who have achieved high school graduation and are regularly confronted with symbolic numbers may still face a cognitive cost to perform numerical judgements on them. In particular, the results suggest that the poor arithmetic skills of adults with MLD may actually hide a primary deficit in Arabic digit processing, which is likely to affect a wide range of basic numerical activities in everyday life.

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4 In contrast, our study shows no evidence of an impaired ability of adults with MLD in Arabic
5 digit recognition. Indeed, their performance in an Arabic digit lexical decision task does not differ from
6 the performance of typically developed adults after controlling for response speed differences in a choice
7 reaction time task used as a control condition. Bayesian analyses further indicated that the data are best
8 explained by a model that does not assume a specific impairment in recognizing Arabic digits. Hence,
9 the second implication of our results is that adults with MLD can experience difficulties in the processing
10 of Arabic digits although they show no sign of digit visual recognition deficit. This finding holds even
11 when contrasting digit and letter recognition or trials of different levels of difficulty (noisy vs.
12 transparent background). The main effect of visual noise on RTs proves that the lexical decision task is
13 sensitive to the perceptual context and should reflect a core deficit in visual digit recognition if it were
14 present. The COMPARISON task was responded faster than the DIGIT-DECISION decision task by
15 participants of both groups. This observation supports the external validity of our assessment of Arabic
16 digit processing because a similar difference was observed between digit comparison and lexical
17 decision in the study of Lafay and colleagues (2018). This RT difference could be due to the fact that
18 the magnitude comparison task was more familiar to the participants. It could also be due to the fact that
19 the magnitude comparison task required pressing the key on the side of the largest number (e.g., left or
20 right side), whereas the lexical decision task involved arbitrary stimulus-response mapping (e.g., left if
21 digit or right if pseudo-digit). The latter may also explain the RT difference observed between the two
22 choice reaction time tasks that also differed in response mapping. Thus, despite the limitations inherent
23 to the convenience sample used in the present study, the tasks proved sufficiently sensitive and the
24 results of the different analyses converged to show that the difficulties of adults with MLD in Arabic
25 digit processing may occur in the absence of any deficit of digit visual recognition.
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50 This finding contradicts the hypothesis that the difficulties of adults with MLD in Arabic digit
51 processing find their origin in a pre-semantic deficit affecting digit visual recognition. In a former study,
52 Lafay and colleagues (2018) reported that children with MLD were less accurate than their peers in a
53 lexical decision task on Arabic digits. However, this difference disappeared when non-verbal reasoning
54 and reading skills were included as covariates in the statistical analysis. The covariate effect of reading
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4 fluency on digit recognition might reflect a general impairment in symbol recognition affecting both
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6 reading and number processing. While impaired symbol recognition appears as a plausible explanation
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8 of the co-morbidity between reading and arithmetic deficits in some children, it cannot account for the
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10 arithmetic difficulties of adult participants in our study because they showed no digit recognition deficit
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12 anyway. The possibility remains that impaired symbol recognition could be the common denominator
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14 of dyslexia and dyscalculia in a subgroup of individuals not represented in our sample. In the study of
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16 Lafay and colleagues (2018), the effect of MLD on digit recognition was also mediated by the reasoning
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18 skills, suggesting that their difficulty in digit recognition could reflect sub-optimal reasoning skills. If
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20 so, then it is no surprise that the present study reveals no impairment in digit recognition since the MLD
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22 participants performed as well as control participants in the verbal reasoning test “Similitudes” of the
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24 WAIS-IV (Wechsler, 2011), in line with the inclusion criterion that required them to obtain a score
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26 superior to the mean of the normative sample minus 2. Finally, the discrepancy between our results and
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28 those of Lafay and colleagues (2018) could be explained by the nature of the distractors used in the digit
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30 recognition task. The inability of MLD to differentiate letters and digits in the study of Lafay and
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32 colleagues (2018) could indeed reflect impaired processing of the character category representation
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34 (McCloskey & Schubert, 2014). According to the model of McCloskey and Schubert (2014), a deficit
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36 at the category level should not hinder processing at the level of digit identification because they operate
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38 in parallel. Our study was specifically designed to investigate digit recognition in reference to the
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40 allograph representation. In contrast, the study of Lafay and colleagues (2018) does not include a
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42 recognition task that would eliminate the category level. Testing the different levels of processing could
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44 shed light on the respective difficulties of children and adults in visual recognition of digits.
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49 More generally, future studies should consider the hypothesis that a difficulty to recognize
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51 Arabic digits may compromise the acquisition of efficient numerical skills in childhood, leaving them
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53 durably affected even though the visual difficulty resolves later during development. This hypothesis
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55 predicts poor digit lexical decision performance in children with MLD, but not necessarily in adults with
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57 MLD since their digit visual recognition deficit may get attenuated over time with regular exposure to
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59 Arabic digits. However, the impact on numerical acquisitions would remain visible across lifespan,
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4 creating a gap in symbolic number knowledge, as suggested by the dissociated effect of MLD on
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6 magnitude comparison and lexical decision in our adult study. Further developmental studies are needed
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8 to investigate the crosstalk between the visual recognition of Arabic digits and the formation of
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10 magnitude representations across development, and to test the hypothesis of mutual interference during
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12 a critical period of acquisition. Decisive evidence could also come from training studies that aim to
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14 improve digit visual recognition skills in children while measuring the effect on other numerical
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16 performance. In the absence of further evidence, our data are best explained by the view that MLD is
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18 due to a semantic deficit affecting the processing stages where a meaning is assigned to numerical
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20 symbols. The deficit could be the expression of a general impairment of the ANS (Wilson & Dehaene,
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22 2007), or a selective impairment affecting the exact representation of symbolic numbers (Marinova et
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24 al., 2021; Noël & Rousselle, 2011; Roggeman et al., 2007) or the access to the representation of
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26 numerical magnitude from Arabic digits (Rousselle & Noël, 2007). Our data are compatible with all
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28 these hypotheses, as far as they do not associate the impaired access or representation of digit magnitude
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30 with a dysfunction at the allographic level where a symbol is recognized as one of the digits.
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34 Finally, our results converge with a number of studies showing that participants with MLD
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36 suffer from a recurrent slowdown in cognitive tasks, adding up to their difficulties with symbolic number
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38 processing, as evidenced here by the higher RTs observed in the control choice reaction time tasks (see
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40 also Censabella & Noël, 2005; Lafay et al., 2018; Rousselle & Noël, 2007; Wang et al., 2018). Domain-
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42 general deficits of cognitive control, attention, working memory or processing speed have been reported
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44 in MLD (Fias et al., 2013; Rubinsten & Henik, 2009; Wang et al., 2018). In our and other studies in
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46 individuals with MLD (Cheng et al., 2018), the slowdown observed in non-numerical tasks that simply
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48 require matching low-level perceptual attributes with binary motor responses is indeed compatible with
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50 domain-general deficits affecting background cognitive processing. However, their nature and
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52 relationship to dyscalculia remains to be fully understood.
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56 In conclusion, the present study showed that adults with a history of mathematical learning
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58 disability continue to experience difficulties not just in arithmetic tasks but also in basic numerical tasks
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60 such as digit comparison. The study further showed that these difficulties are not associated with any

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4 impairment in the visual recognition of Arabic digits, as indexed by lexical decision performance,
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6 placing an important constraint on existing accounts. The possibility remains that a weakness in visual
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8 digit recognition may hinder the acquisition of efficient symbolic numerical skills in the early stages of
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10 development, before eventually resolving later on. This possibility calls for further investigation, in
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12 children in particular.
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46 **Data availability statement**

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49 The data supporting the results will be made publicly available on OSF under the CC BY license.
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Figure Captions

Figure 1. Examples of stimuli in the Arabic digit comparison task (A), in the digit lexical decision task (B), and in their respective control conditions.

Figure 2. Mean reaction time (RT) in the Arabic digit comparison task (COMPARISON), relative to the matched choice reaction time task (CRT-COMP), in the control group (CG) and in the group of participants with mathematical learning disability (MLD). Participants with MLD show a specific increase of their RTs in the Arabic digit comparison task compared to controls. *** $p \leq .001$

Figure 3. Distribution of reaction times (RTs) in the Arabic digit comparison task, with respect to the matched choice reaction time task, for the participants with mathematical learning disability (MLD) and for those of the control group (CG). Seven out of the 19 participants with MLD are outside the 95% confidence interval along the regression line describing the performance of CG participants. Note this is also the case for one control participant (CG2).

Figure 4. Mean reaction time (RT) in the digit lexical decision task (DIGIT-DECISION), relative to the matched choice reaction time task (CRT-DEC), in the control group (CG) and in the group of participants with mathematical learning disability (MLD). Participants with MLD show no specific increase of their RTs in the digit lexical decision task compared to controls.

Figure 5. Difference in reaction time (dRT) between the digit comparison task and the matched choice reaction time task (A) and between the digit decision task and the matched choice reaction time task (B). Participants are ranged from the lowest to the highest. In blue: control participants; in light grey: mean of the control participants; in red: the seven participants with mathematical learning disability (MLD) tagged as out of the range of controls on Figure 3; in yellow: other participants with MLD.

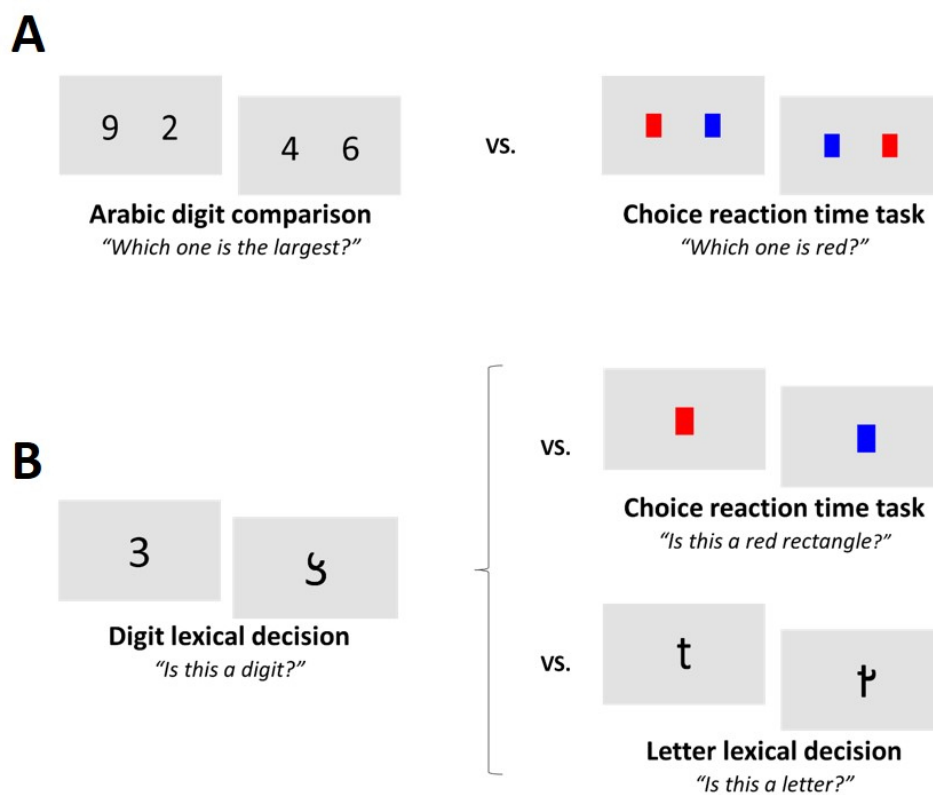


Figure 1. Examples of stimuli in the Arabic digit comparison task (A), in the digit lexical decision task (B), and in their respective control conditions.

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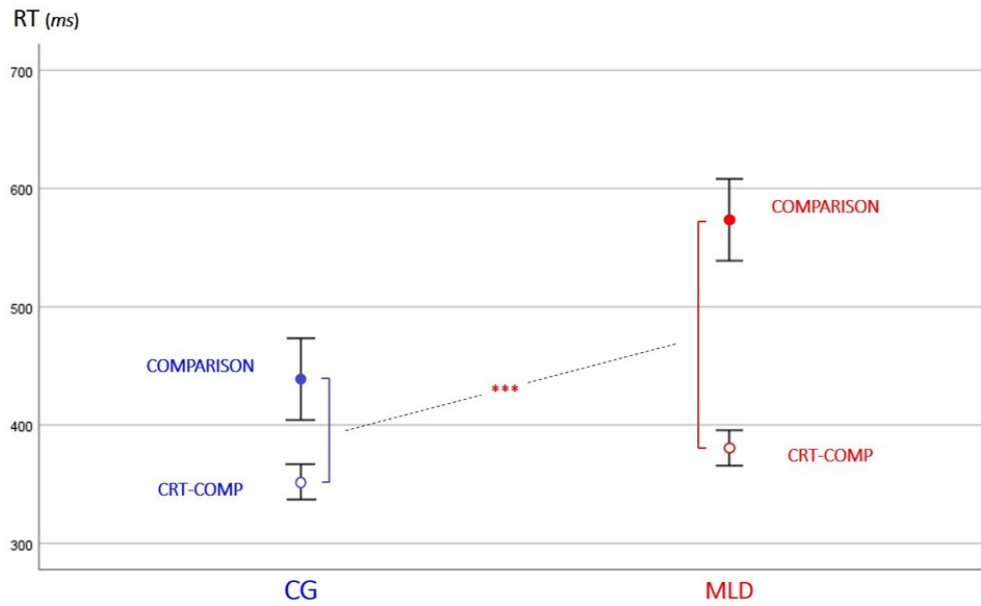


Figure 2. Mean reaction time (RT) in the Arabic digit comparison task (COMPARISON), relative to the matched choice reaction time task (CRT-COMP), in the control group (CG) and in the group of participants with mathematical learning disability (MLD). Participants with MLD show a specific increase of their RTs in the Arabic digit comparison task compared to controls. *** $p \leq .001$

81x49mm (300 x 300 DPI)

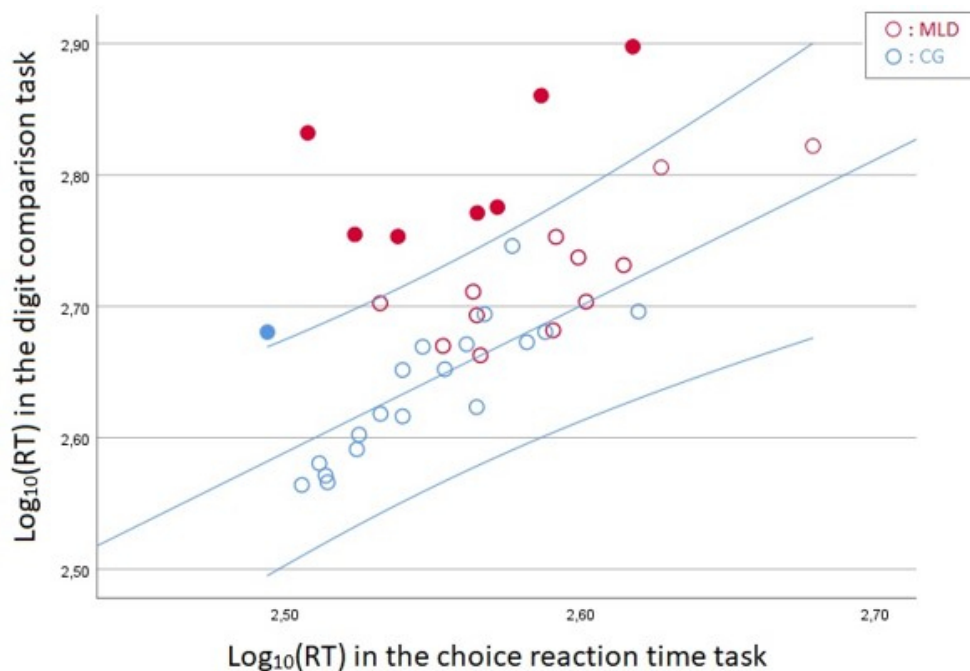


Figure 3. Distribution of reaction times (RTs) in the Arabic digit comparison task, with respect to the matched choice reaction time task, for the participants with mathematical learning disability (MLD) and for those of the control group (CG). Seven out of the 19 participants with MLD are outside the 95% confidence interval along the regression line describing the performance of CG participants. Note this is also the case for one control participant (CG2).

50x34mm (300 x 300 DPI)

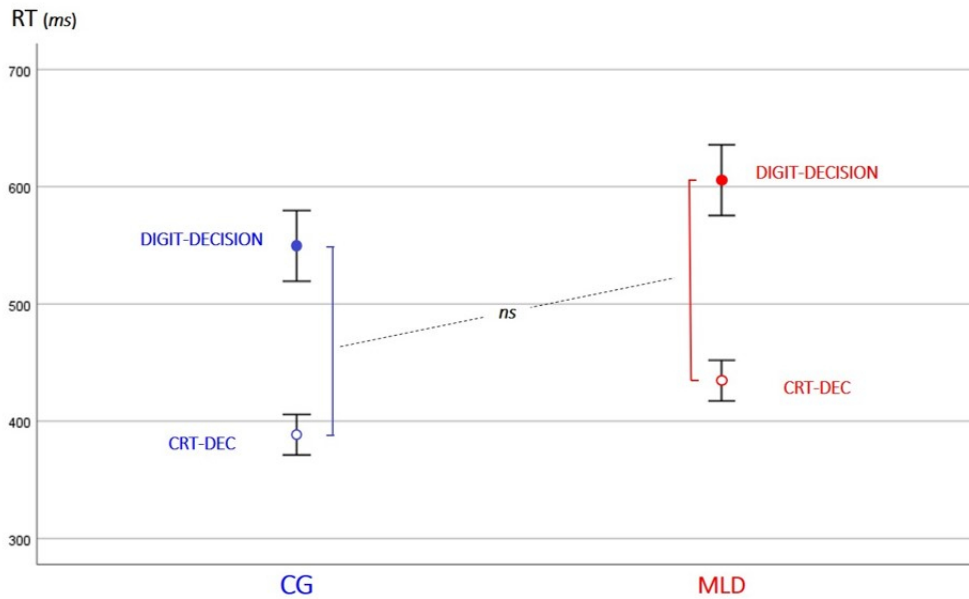


Figure 4. Mean reaction time (RT) in the digit lexical decision task (DIGIT-DECISION), relative to the matched choice reaction time task (CRT-DEC), in the control group (CG) and in the group of participants with mathematical learning disability (MLD). Participants with MLD show no specific increase of their RTs in the digit lexical decision task compared to controls.

79x48mm (300 x 300 DPI)

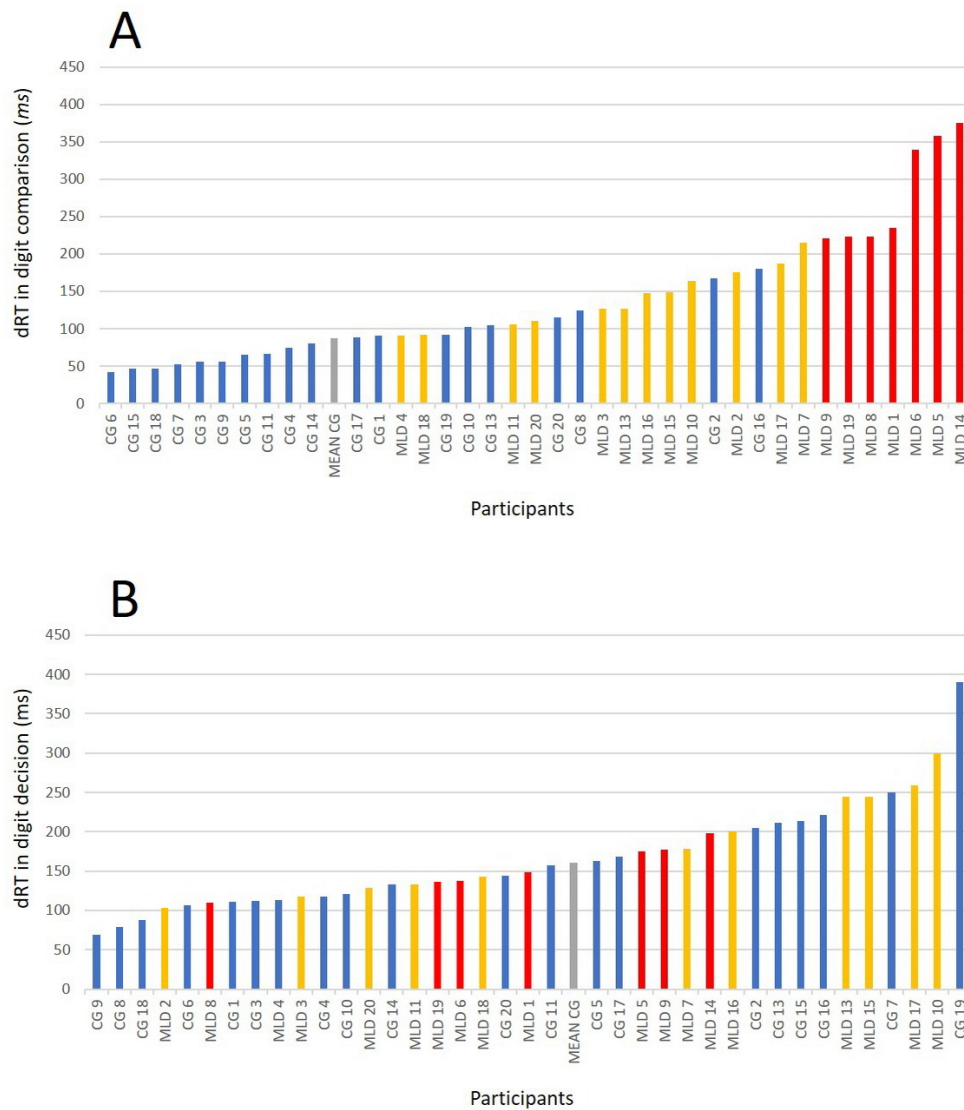


Figure 5. Difference in reaction time (dRT) between the digit comparison task and the matched choice reaction time task (A) and between the digit decision task and the matched choice reaction time task (B). Participants are ranged from the lowest to the highest. In blue: control participants; in light grey: mean of the control participants; in red: the seven participants with mathematical learning disability (MLD) tagged as out of the range of controls on Figure 3; in yellow: other participants with MLD.

195x222mm (150 x 150 DPI)

Table 1: Description of MLD and CG groups.

	MLD	CG	Tests	<i>p</i>
<i>Socio-demographic variables</i>				
Sex	19 ♀	19 ♀		
Manual dominance	16 R; 3 L	16 R; 3 L		
Age (<i>y-o</i>)	<i>M</i> = 23.18, <i>SD</i> = 2.32	<i>M</i> = 23.09, <i>SD</i> = 2.26	<i>t</i> (36) = .13	<i>p</i> = .901
Number of school years	<i>Mdn</i> = 15, range: 12-18	<i>Mdn</i> = 15, range: 12-17	<i>U</i> = 162	<i>p</i> = .603
<i>WAIS IV Measures</i>				
WAIS "Similitudes"	<i>M</i> = 12.16, <i>SD</i> = 1.86	<i>M</i> = 13, <i>SD</i> = 1.97	<i>U</i> = 130	<i>p</i> = .146
WAIS "Symbole"	<i>M</i> = 9.63, <i>SD</i> = 2.27	<i>M</i> = 11.90, <i>SD</i> = 1.91	<i>U</i> = 86	<i>p</i> = .005
<i>Arithmetic Measures</i>				
Arithmetic battery accuracy (<i>z</i>)	<i>M</i> = -2.12, <i>SD</i> = 2.22	<i>M</i> = .47, <i>SD</i> = .64	<i>U</i> = 41	<i>p</i> < .001
Arithmetic battery speed (<i>z</i>)	<i>M</i> = -2.09, <i>SD</i> = 1.65	<i>M</i> = .29, <i>SD</i> = .65	<i>t</i> (23.49) = 5.85	<i>p</i> < .001
TTA total fluency (<i>z</i>)	<i>M</i> = -2.17, <i>SD</i> = 1.20	<i>M</i> = .69, <i>SD</i> = .68	<i>t</i> (36) = 9.05	<i>p</i> < .001

Table 2: Mean and standard deviation of the individual accuracy rates (ACC) and correct reaction times (RT) as a function of group and task.

	N	CRT-COMP		CRT-DEC		COMPARISON		DIGIT-DECISION		LETTER-DECISION	
		ACC	RT	ACC	RT	ACC	RT	ACC	RT	ACC	RT
MLD	19	98.6 (2.8)	380.7 (36.5)	97.0 (2.9)	434.7 (39.7)	96.5 (3.4)	573.5 (90.9)	97.1 (2.9)	605.7 (52.3)	96.7 (2.6)	612.2 (55.6)
CG	19	98.6 (2.0)	352.0 (27.0)	96.5 (4.2)	388.5 (34.7)	96.5 (2.6)	438.8 (52.7)	96.9 (2.2)	549.6 (75.3)	97.6 (1.9)	541.5 (53.7)

Note. ACC are expressed in %; RT in ms.

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