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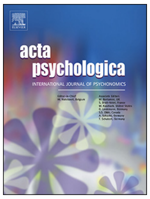

A shared code for Braille and Arabic digits revealed by cross-modal priming in sighted Braille readers

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ABSTRACT

Quantities can be represented by different formats (e.g. symbolic or non-symbolic) and conveyed via different modalities (e.g. tactile or visual). Despite different priming curves: V-shape and step-shape for place and summation coded representation, respectively, the occurrence of priming effect supports the notion of different format overlap on the same mental number line. However, little is known about tactile-visual overlap of symbolic numerosities i.e. Braille numbers to Arabic digits on the magnitude number representation. Here, in a priming experiment, we tested a unique group of sighted Braille readers to investigate whether tactile Braille digits would activate a place-coding type of mental number representation (V-shape), analogous to other symbolic formats. The primes were either tactile Braille digits presented on a Braille display or number words presented on a computer screen. The targets were visually presented Arabic digits, and subjects performed a naming task. Our results reveal a V-shape priming function for both prime formats: tactile Braille and written words representing numbers, with strongest priming for primes of identical value (e.g. "four" and "4"), and a symmetrical decrease of priming strength for neighboring numbers, which indicates that the observed priming is due to identity priming. We thus argue that the magnitude information is processed according to a shared phonological code, independent of the input modality.

1. Introduction

Number processing is a fundamental achievement of the human brain and various non-human animal species (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Feigenson, Dehaene, & Spelke, 2004). Quantities can be represented either symbolically (e.g. Arabic digits, words) or non-symbolically (e.g. as collections of dots). There is an ongoing debate about whether or not these converge on the same mental representation (Kadosh & Walsh, 2009 vs. Nieder & Dehaene, 2009). Beyond the different formats, numerical information can be conveyed via different modalities (e.g. visual vs. auditory). The question to what extent different modalities converge on a common underlying mental magnitude representation also remains unresolved (Knops, 2017). Especially, little is known about tactile-visual overlap of symbolic numerosities i.e. Braille numbers to Arabic digits on the magnitude number representation.

A few studies to date have investigated how tactile number information is processed. These studies provided important insights into cross-modal number processing; however, they used non-symbolic tactile number coding (number of stimulated fingers; Krause, Bekkering, & Lindemann, 2013; Cohen, Naparstek, & Henik, 2014; Sixtus, Lindemann, & Fischer, 2018). To our knowledge, number coding in a symbolic tactile notation – Braille numbers – has not previously been investigated. Similar to letters, Braille numbers are represented by a combination of dots that correspond to the first 10 letters of the Braille alphabet, preceded by a number indicator (see Fig. 2C). For example, the number 6 is represented by the Braille letter 'F', preceded by the number indicator. Learning to read Braille numbers consists thus of learning new associations for existing Braille letter symbols.

Numbers are thought to be represented on a mental number line (MNL) which is spatially organized on a continuum of numerical magnitudes where, for cultures with the left-to-right writing systems, smaller numbers are to the left of larger numbers (e.g., Dehaene & Changeux, 1993; Dehaene, Dupoux, & Mehler, 1990; Restle, 1970).

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Previous studies suggest that symbolic number formats are represented in a place-coding regime (Roggeman, Verguts, & Fias, 2007; Verguts, Fias, & Stevens, 2005). In place coding, activation peaks at a target position on the number line (numerical magnitude is coded by position), while the neighboring numbers are activated with decreasing strength (Roggeman et al., 2007; Verguts et al., 2005; Verguts & Fias, 2004). A different type of coding, called summation coding, is observed for non-symbolic number notations such as collections of dots (1 = one dot, 2 = two dots, 3 = three dots, and so on). In the summation coding regime, all number line entries are activated until the target number is reached (numerical magnitude is coded by the sum of activated entries). The latter type of coding could be expected if Braille students identified Braille numbers (e.g. 5) by counting up to the ordinal position of the corresponding letter (e) in the alphabet ("a, b, c, d, e").

The actual type of coding can be revealed by priming studies. Varying the numerical relation between the prime and target number in number-naming paradigms produces differing performance patterns, depending on the underlying code that has been activated by the prime (Koechlin, Naccache, Block, & Dehaene, 1999; Reynvoet, Brysbaert, & Fias, 2002; Roggeman et al., 2007). When the number prime activates a place-code, naming latencies increase with increasing numerical distance between prime and target, which leads to a V-shaped priming function. Two scenarios are possible for a V-shaped function. The first one is distance-related priming: lowest naming latencies for no difference: e.g. "four" to "4", slightly larger for "five" to "4", and still larger for "six" to "4"). Such priming reflects true semantic access to the mental number line. In the second scenario, the V-shaped function, is driven by identity priming only: lower latencies (priming) only for identical numerosity (e.g. "four" to "4") but no effect of distance (same long latencies for "five" to "4", and "six" to "4"), a "narrower V-shape". This shape most likely reflects a type of priming that does not have to be semantic, and can be based on phonological access only. When the prime number activates a summation code, naming latencies are characterized by a step-like priming function where each numerical quantity activates all entries up to and including the presented quantity. For example, upon the presentation of a 4-dot prime, the entries 1, 2, 3, and 4 are activated, thus leading to a step-wise priming function with enhanced performance for all smaller and equal target numerosities.

In the Triple Code Model (TCM), numerical information is thought to be internally represented by three separate but interacting codes: 1) a verbal number code, activated in linguistically mediated operations like number naming, counting, and retrieval of arithmetic facts from long-term memory; 2) the visual number code that allows recognition of Arabic digits and multi-digit numbers; and 3) an analogue magnitude code that represents numerical quantity information (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Molko et al., 2003) in an approximate manner. According to the TCM, a visual number code (Fig. 1) is activated during visual recognition of e.g. Arabic numbers. However, if Braille numbers and Arabic digits would not share a code, we would have to assume another, i.e. tactile code in the Triple Code Model.

Here, we investigated whether the acquisition of tactile Braille digit reading leads to a place-coding type of mental number activation. Such an activation could be achieved by two mechanisms: Braille numbers could be mapped directly on a semantic code i.e. co-activate it (Fig. 1 path A), or they could be mapped onto a phonological code i.e. co-activate it without automatic activation of a semantic code (Fig. 1 path B). Alternatively, if the strategies used by Braille number readers involve intermediate steps (e.g. counting up to the corresponding letter), the result would be a summation-code type of mental number activation.

We used Braille digits presented in the tactile modality as primes, and Arabic digits as targets (Fig. 2). As a control, we used number words as primes, and Arabic digits as targets, both presented visually (e.g. Naccache & Dehaene, 2001; Reynvoet et al., 2002). Our reasoning was that if we observe the same priming pattern, i.e. a V-shape function for the two types of priming, it would indicate that symbolic numerosities are represented in an abstract format and can be accessed regardless of the modality or notation. Alternatively, counting up to the respective letter upon the presentation of Braille primes would lead to different priming functions: step-like for Braille primes and V-shaped for number word primes.

2. Materials and methods

2.1. Participants

Twenty female subjects (mean age = 25; age range = 22–32) participated in the experiment. All participants were right-handed, monolingual with normal or corrected to normal vision. The participants were students or college graduates with minimum 3 years of higher education (mean = 5 years; range = 3–12 years). The group was recruited from participants of two previous projects that were performed in 2016 and 2017 and which included a nine-month Braille-reading course. During this Braille course, participants acquired tactile recognition of all Braille letters in the Polish alphabet (for details, see Bola et al., 2016). For the purpose of the current experiment, all participants attended a 3-week course focused specifically on reading Braille numbers. The course, which was designed and carried out by an experienced Braille teacher that also co-designed the previous course, took place in May 2018, i.e. either one or two years after the main nine-month course. Since numbers in the Braille alphabet are letter symbols from A to J preceded by a number indicator (e.g. number two is a letter b preceded by a number indicator), participants needed only a three-week course to automatize recognizing Braille numbers. Similarly to the previous one, the course relied primarily on participants' individual work. At the beginning of the course they were given 20 exercises, each printed on a single sheet. They were asked to complete one exercise per day, blindfolded, and then to check their results visually. During the first two weeks of the course, a class was held twice a week, during which participants were given a subsequent set of Braille exercises, received detailed and personalized instruction about completing them, practiced a sample set of exercises in the class and received personalized feedback from the instructor. During the last week of the course they met individually with the Braille teacher to resolve any potential issues (e.g. regarding proper Braille reading technique) and practice on the Braille display used in the main experiment. Before and after the Braille number recognition course, we tested the participants' Braille numbers, letters and words recognition and tactile acuity with different tests that we list below. Our main goal here, was to test the participants' ability to recognize Braille numbers, however, additionally we tested whether we would observe an additional improvement in their general Braille reading skills and thus their overall fluency in Braille reading. Despite being right-handed, seven of the 20 subjects read with their left hand. This phenomenon – a preference for reading Braille with the non-dominant hand – is common and well described in the population of blind subjects (e.g. Millar, 1997) and has been also reported in sighted Braille readers (Bola et al., 2016). The study was approved by the Jagiellonian University Ethics Committee. A written informed consent was obtained from all subjects before the experiment. Participants were reimbursed for taking part in the study.

2.2. Braille reading speed tests

The subjects' Braille reading speed was tested twice: at the beginning of the course and at the end of it, but before the main priming experiment. To test the subjects' Braille reading speed in both visual and tactile modalities, we used four different paper tests. Since there are no standardized tests measuring tactile or visual Braille reading speed in Polish, we created a tactile Braille reading test of single numbers (consisting of 6 rows of Braille numbers), a tactile Braille reading test of single letters (consisting of 6 rows of single Braille letters in Polish alphabet), a tactile Braille reading test of whole words

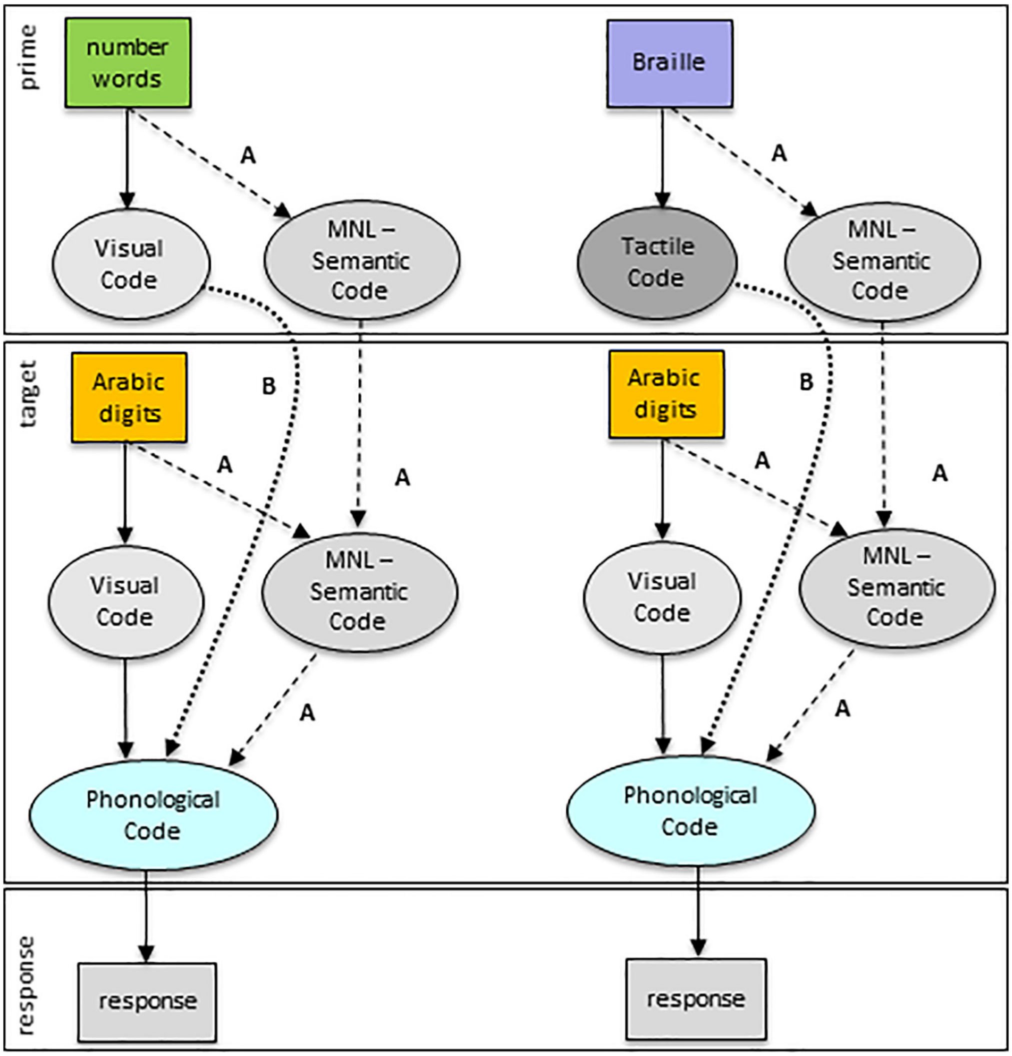

Fig. 1. Processing model. The model includes two different number codes of the prime: Visual Code for number words and Tactile Code for Braille digits. Our question was that if primes (tactile Braille and number words) and targets (Arabic digits) share a code, what is the nature of the activated code? The model thus depicts two alternative paths of processing from the prime through the target up to the response (A) via semantic code or directly to (B) phonological code.

(consisting of 4 rows of 4–6 letter long words, printed in tactile Braille) and a visual Braille reading speed test (consisting of 30 words, 4–6 letters long, printed in a visual Braille font).

2.3. *Visual reading speed test*

To test the subjects' visual reading speed we used a test previously designed by Bola et al. (2016), which consists of a 400-word passage from the book “Farsa Panny Heni” by Maria Rodziewiczówna printed on paper. After reading the text silently, subjects were given a test, printed on paper, consisting of 10 multiple choice questions concerning the text. The overall time needed to read the text as well as the accuracy of the given answers were measured.

2.4. *Tactile acuity test*

Additionally, we tested the tactile acuity of participants' index finger on the reading hand using the tactile acuity grating orientation task (Van Boven, Hamilton, Kauffman, Keenan, & Pascual-Leone, 2000). Following Van Boven et al. (2000) a set of eight hemispherical plastic domes with gratings in their surfaces was used to stimulate index fingertip of the reading hand. Grates on domes' surfaces form two parallel rows of bars and grooves that can be aligned along or perpendicularly to the long axis of the finger. Each dome was presented for 1.5 s and participants were asked to name verbally the orientation of the rows: either perpendicular or horizontal (two-alternative forced choice paradigm). The experimenter noted down the given answers.

2.5. *Braille number recognition test*

For the purpose of the main experiment we tested the participants' ability to recognize Braille numbers on the Braille Display (BraillePen 12 Touch, a portable 12-cell Braille display http://www.harpo.com.pl/), which we then used in the main experiment. In this test, participants were asked to read aloud a Braille number (range = 0–9; number of repetitions = 20 per number) that appeared on the Braille display for a varying amount of time (300 ms, 600 ms or 900 ms).

Following the aforementioned three-week course, the subjects performed the priming experiment, the details of which are given below.

2.6. *Main experiment — stimuli*

Fig. 2 shows the stimuli used in the main experiment. We used numbers from 2 to 6 (following Reynvoet & Brysbaert, 1999; Reynvoet et al., 2002; Roggeman et al., 2007). Since the number 1 in Braille is the only number consisting of only one dot, to avoid an obvious

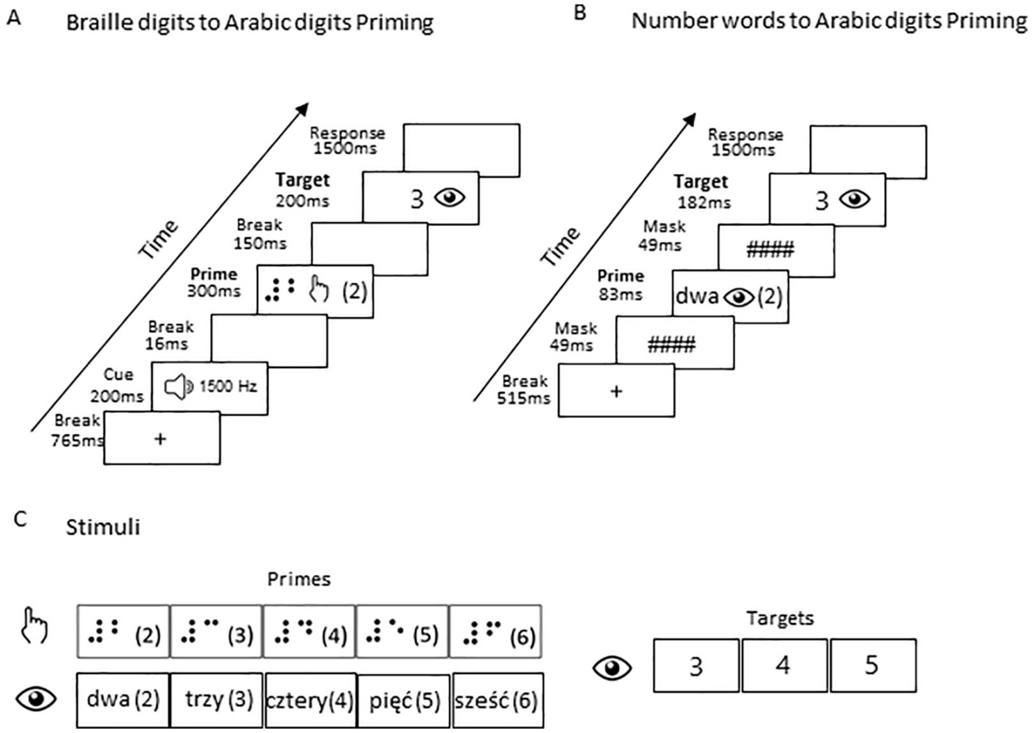

Fig. 2. Experimental paradigm. (A) Tactile Braille digit to Arabic digit priming and (B) number word to Arabic digit priming. (C) Stimuli used in the experiment: primes-tactile Braille digits and visual number words; targets — Arabic digits. Participants were asked to name the target Arabic number displayed on the computer screen in all trials in all conditions.

correspondence (1 dot — number one), this number was excluded. Primes were either tactile Braille numbers (i.e. a letter preceded by a number indicator — a combination which stands for a number in the Braille alphabet) displayed on the Braille display, or visual number words (i.e. "sześć") displayed on the computer screen. Targets were always Arabic digits (range = 3–5; see Fig. 2C). Visual stimuli (number words and Arabic digits) were presented in white against a black background in courier font with a size comparable to the Braille numbers (font size: 36, see Fig. 2A).

2.7. *Main experiment — apparatus*

Stimuli were presented on a 13 in. screen (DELL) and on a Braille Display (BraillePen 12 Touch 12, Harpo, Poznan, Poland, http://www.harpo.com.pl/) using Presentation Software (a stimulus delivery and experiment control program for neuroscience, Neurobehavioral Systems, Berkley, USA, https://www.neurobs.com/).

2.8. *Main experiment — procedure*

Two experimental conditions were tested. In both conditions, the target was presented visually as an Arabic digit (3, 4 or 5). In the Braille condition, the prime was presented as a Braille digit (in the tactile modality, Fig. 2A), while in the number words condition the prime was presented as a written number word (in the Latin alphabet) representing a number (in the visual modality, Fig. 2B). For each condition, we used 3 targets (3, 4, 5) × 5 primes (2–6) = 15 possible combinations of prime–target values (Fig. 2C), which were presented in a random order. The conditions were presented in blocks. There were two blocks of each experimental condition (4 blocks in total), counterbalanced between subjects. Each block consisted of 150 trials (10 repetitions of each of the 15 target-prime combinations). In the tactile condition we presented the participants with 15 additional catch trails (trial + additional naming of the prime after a "?" occurred to randomly check if the participant was paying attention to the prime and as an additional measure of the accuracy in recognizing Braille digits).

Before the first block of each condition, 65 practice trials were given to familiarize the participants with the procedure. In the Braille condition each trial began with the presentation of a fixation cross for 765 ms followed by a 200 ms beep and 16 ms break. The prime was then presented for 300 ms so that it could be perceptible (see Braille number recognition test). The prime was followed by a 150 ms break. Finally, the target was presented for 200 ms, after which participants named aloud the indicated quantity. Subjects had 1500 ms to respond (Fig. 2A). The additional catch trials were introduced to measure the accuracy of tactile prime recognition. In these trials, after the basic trial, there was a 150 ms break after the target, and then a question mark appeared for 2000 ms, during which the participants were asked to name the prime. In the number words condition (designed after Roggeman et al., 2007) each trial began with a fixation cross for 515 ms. Then we presented a mask for 49 ms, followed by the prime presented for 83 ms. The mask was then presented for 49 ms and, finally, the target was presented for 182 ms, after which participants named aloud the indicated quantity. Subjects had 1500 ms to respond (Fig. 2B). The mask was applied only in the number words condition i.e. before and after the visual prime, due to the occurrence of an afterimage after visual stimulus presentation, a phenomenon unique for the visual stimuli not the tactile ones.

2.9. *Main experiment — data analysis*

To establish a statistical difference in the shapes of the priming curves, we first performed a repeated-measures ANOVA with prime notation (number words vs. Braille), prime and target value on mean RTs. We then performed a repeated-measures ANOVA on mean RTs separately for Braille and number words. In all repeated-measures ANOVAs, we tested for violations of sphericity using Mauchly's test. To test whether the V-shape priming curve was determined by identity priming or a distance-related priming we ran the analysis in both prime notations for the zero distance and its two most neighboring distances (-1 and 1). To keep the same target–prime distance, in all conditions we restricted our analyses to 6 prime-target combinations. To further test for semantic priming, we removed target-prime distance 0 and ran regression analysis for both prime notations. Nevertheless, following others (Roggeman et al., 2007) we began with a repeated-measures ANOVA that included all distances.

Subsequently, we followed with a regression analysis to establish the difference in regression coefficients for V-shape and step-like predictors in both prime notations (Braille and number words). The V-function predictor had a value equal to the absolute value of the target value — prime value. If the prime value was greater or equal to the target value, then the step-function predictor had a value equal to -1, and a value equal to $+1$ in cases in which the prime value was smaller than the target value. Following previous studies (Hesselmann, Darcy, Sterzer, & Knops, 2015; Hesselmann & Knops, 2014; Reynvoet et al., 2002; Roggeman et al., 2007), we fitted the regression equations with two predictors which coded for a V-function and a step-function, respectively. Additionally, we added the target value and an intercept to the regression, which was run for each participant separately (Hesselmann et al., 2015; Hesselmann & Knops, 2014; Lorch & Myers, 1990; Roggeman et al., 2007). Below we provide the regression formula:

$y = b0 + b1(x1) + b2(x2) + b3(x3)$
y — dependent variable: reaction times (RTs).
$b0$ — the y-intercept.
$b1$, $b2$, $b3$ — unstandardized B coefficients.
$x1$ — independent variable 1 (V-shape predictor).
$x2$ — independent variable 2 (step-shape predictor).
$x3$ — independent variable 3 (target predictor).

A positive regression coefficient for the V-function predictor means that larger |prime–value minus target–value| distances lead to higher RTs and in this way this predictor codes for the presence of a V-shape and i.e. symmetrical decrease of the activation strength. A positive regression coefficient for the step-function predictor indicates that the shape of the priming curve can be described by a step-function in which prime values larger than or equal to the target value lead to faster RTs. The coefficient patterns for the V-function and the step-function for each prime notation were then compared with a paired *t*-test. As previously, we began with the regression including all the target–prime distances (-3 up to 3, including zero distance) and followed with the regression restricted to the two most-neighboring distances. We compared the pattern of coefficients for the V-function and the step-function for each prime notation with a paired t-test, and the V-function coefficients with zero.

3. Results

3.1. Braille reading speed tests

In all reading speed tests we report the number of correctly read numbers/letters/words in the allotted time. At the onset of the three-week Braille course, the mean tactile single Braille number-reading speed among the participants was 11 numbers per minute (NPM) (SEM = 1.49; range = 3–28). The mean tactile single Braille letter-reading speed among the participants was 15.9 letters per minute (LPM) (SEM = 0.94; range = 7–26). The mean tactile Braille word-reading speed among the participants was 4.9 words per minute (WPM) (SEM = 0.68; range = 1–14). The mean visual Braille word-reading speed among the participants was 19.6 words per minute (WPM) (SEM = 1.47 range: 8–37). After the Braille course participants reached an averaged performance of 30.8 numbers per minute (NPM) (SEM = 2.58 range: 6–49), 18.6 letters per minute (LPM) (SEM = 1.29 range: 12–32), 6.3 words per minute (WPM) (SEM = 0.77 range: 1–14) in the tactile modality and 22.3 words per minute (WPM) (SEM = 1.43 range: 1–18) in the visual modality (Fig. 3A-C).

To directly test for an increase in the Braille reading speed, we ran paired *t*-tests between 'before' vs. 'after' course results from all tests described above. These analyses confirmed that the increase in Braille reading speed was significant in all tests [tactile Braille numbers: t(19) = -8.598, $p < .001$; tactile Braille letters: t(19) = -3.008, $p = .007$; tactile Braille words: t(19) = 3.935, $p < .001$; visual Braille words: t(19) = -4.992, $p < .001$, Fig. 3A–C]. Thus, although the aim of the Braille course was to master and automatize tactile Braille number reading, the results show a significant increase in visual Braille reading speed as well.

3.2. Visual reading speed tests

The mean reading speed of the text with full sentences ("Farsa Pani Heni") was 185 words per minute (WPM) (SEM = 12.83; range: 93–296) which is a standard result for visual reading speed in skilled adults (e.g. Bola et al., 2016; Hunziker, 2006). The subjects' visual reading speed was not correlated with any of the tests measuring Braille reading speed [tactile Braille numbers: r(20) = -0.136, $p = .566$; tactile Braille letters: r(20) = -0.252, $p = .284$; tactile Braille words: r(20) = -0.138, $p = .563$; visual Braille words: r(20) = 0.236, $p = .317$].

3.3. Tactile acuity test

At the onset of the Braille course, the mean grating orientation threshold for the reading finger was 1.87 mm (SEM = 0.19). By the end of the course, it had reached 1.53 mm [(SEM = 0.16), which represents a significant improvement (t(19) = 2.805, $p = .011$].

3.4. Braille number recognition test

Additionally, we tested participants' ability to recognize Braille numbers on the digital Braille display. Since minute differences exist between the "feeling" of reading Braille on paper vs. on a digital display, the objective of this test was to precisely determine the reading accuracy under conditions identical to those used in the main experiment i.e. Braille numbers recognition on the Braille display. In this test, participants were asked to read aloud a Braille number that appeared on the Braille display for a given time (300 ms, 600 ms or 900 ms). After participating in the Braille course, on average participants recognized 88% (SEM = 1.79; range = 14–20 numbers out of 20 possible) of Braille numbers displayed for 900 ms, 77% (SEM = 4.72; range = 4–19 numbers out of 20 possible) of Braille numbers when displayed for 600 ms, and 74% (SEM = 3.81; range = 10–20 numbers out of 20 possible) of Braille numbers when displayed for 300 ms.

3.5. Priming experiment

Subjects performed at an accuracy of 99.8%. The responses were recorded and analyzed offline, and additionally coded by the experimenter. Due to voice key failure we excluded 5.1% trials. RTs were adjusted for different verbal onset times for the different target numbers. In the pilot phase we measured onset times for naming target numbers: 3, 4, and 5 in 5 participants. Based on that procedure we decided to add fixed 70 ms to all conditions within target number 5. Subsequently, we calculated means and SDs individually for each participant for each condition and excluded all RTs three standard deviations above or below the mean (0.44%).

To control whether the participants recognized tactile primes, we analyzed the accuracy of the performance in the catch trials, in which participants were asked to additionally name the tactile prime that preceded the target. On average, participants correctly recognized 78.75% (SEM = 2.77, range 67–100%) of tactile primes during the experiment. Additionally, although in priming paradigms the subjects' conscious attention to primes is not necessary for the priming effect to occur (e.g. Dehaene et al., 2001; Naccache & Dehaene, 2001), we tested in the pilot phase, whether the visual primes were visible for the participants. We tested 10 independent participants, and all were able to recognize the primes with 100% accuracy. Both Braille and number words are considered symbolic notations and as such should not show any interaction, however, to statistically test this assumption, we performed a repeated-measures ANOVA with prime notation (number

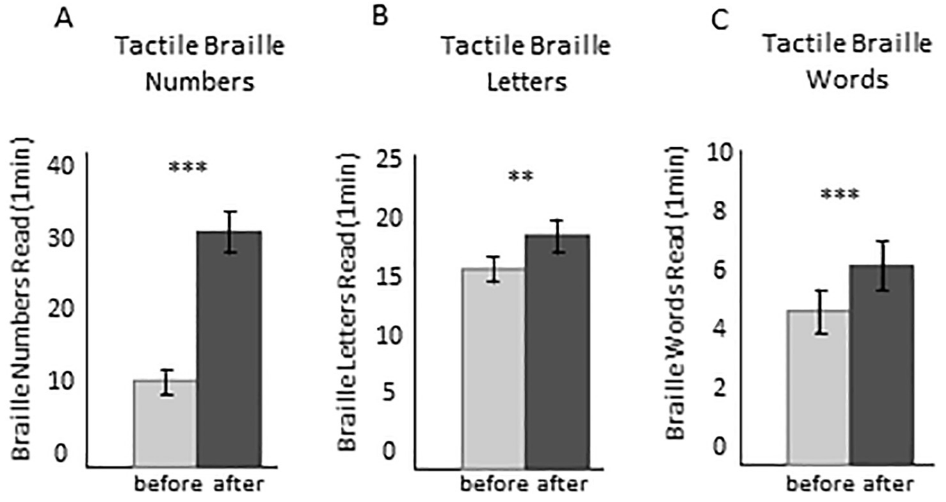

Fig. 3. Braille number reading course. Sighted Braille readers (Bola et al., 2016), were given a three week Braille intensive number reading course. Results of Braille reading tests for tactile Braille reading (A–C) before and after the course. Graphs show the average number of Braille numbers/letters/words (A–C) read per minute. After the Braille course participants read Braille digits three times faster than before the course (A). Significance levels: ****p* < .001, ***p* < .01. Error bars represents S.E.M.

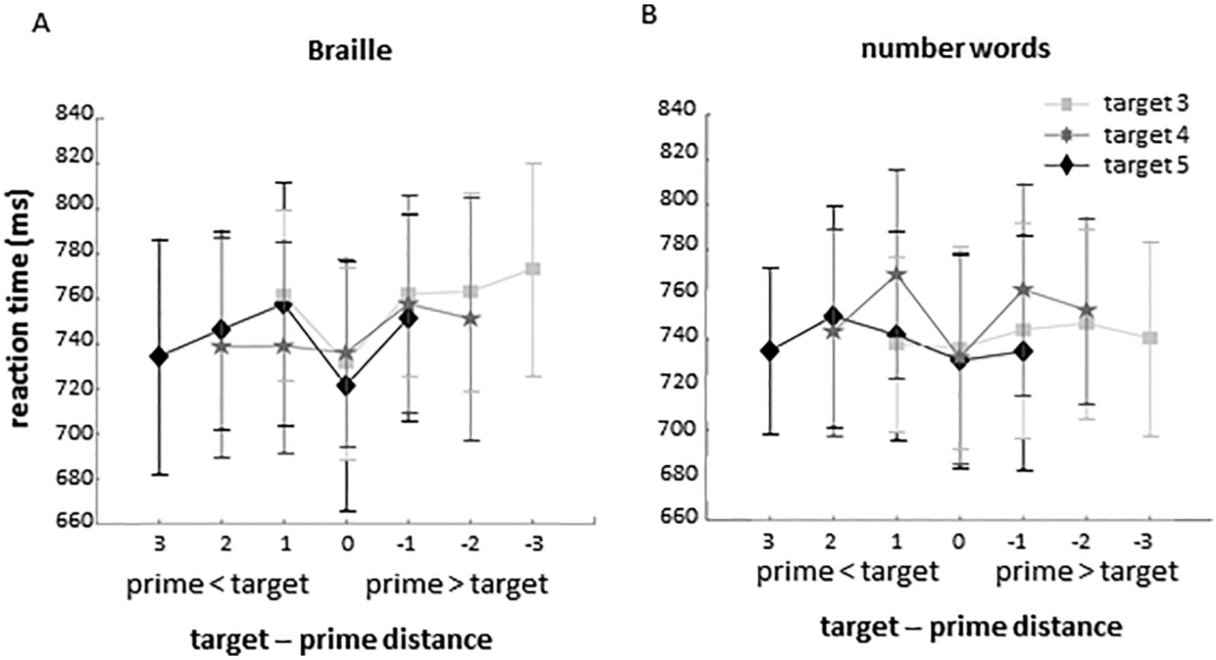

Fig. 4. Priming results. RTs for all prime-target combinations for the two different notations (A) Braille (B) number words. The error bars represent the SE following Cousineau-Morey corrections (Cousineau, 2005; Morey, 2008).

words vs. Braille), prime and target value which revealed no significant main effect (all *ps* > 0.2). However, a significant interaction between prime and target value [F(8,152) = 8.049; *p* < .001] provides the first evidence for a semantic priming effect. Importantly, significant interactions of prime notation with target [F(2,38) = 6.125; *p* = .005] and prime value [F(4,76) = 5.365; *p* = .001] were observed. No other interaction was observed. To follow up on these findings, we computed separate repeated-measures ANOVAs for both prime notations. For Braille primes we observed a significant effect for prime [744, 739, 752, 747 and 758 ms for primes 2–6 respectively; F(4,76) = 2.780; *p* = .033] with no significant effect for target [758, 744, and 742 ms for targets 3–5, respectively; F(2,38) = 1.433; *p* = .251], but a significant interaction between target and prime [F(8,152) = 4.275; *p* < .001]. An analogous repeated-measures ANOVA was then run on mean RTs for the number words condition. This revealed a significant effect for prime [739, 752, 740, 747 and 743 ms for primes 2–6, respectively; F(4,76) = 3.811; *p* = .007], no significant effect for target [741, 752, and 739 ms for targets 3–5, respectively; F(2,38) = 0.706; *p* = .500], but a significant interaction between target and prime [F(8,152) = 3.554; *p* = .001]. Together, these findings suggest that the primes had a significant impact on naming latencies.

To further analyze the impact of the numerical distance between prime and target value, we separately computed a 3 (distance value) × 3 (target value) repeated-measures ANOVA on mean RTs for both Braille and number words. As introduced above, we analyzed the three targets with their identity primes (e.g. target 3 and prime 3), and nearest neighbor primes (e.g. target 5 and primes 4 and 6). For Braille condition, this revealed a significant effect for distance [757, 729, and 753 ms for distance −1, 0, and 1, respectively; F(2,38) = 12.211; *p* < .001] but no significant effect for target [751, 744, and 743 ms for target 3–5, respectively; F(2,38) = 0.424; *p* = .657], or interaction between target and distance [F(4,76) = 1.424; *p* = .234]. We then compared distances −1 and 1 for all targets [target 3: t(19) = 0.045, *p* = .965; target 4: t(19) = 1.732, *p* = .099; target 5: t(19) = −0.810, *p* = .428]. The non-significant results make the assumption highly unlikely that the activation strength was asymmetrical.

The corresponding analysis for number words revealed a significant effect for distance [747, 733, and 750 ms for distance −1 to 1, respectively; F(2,38) = 6.933; *p* = .003] but no significant effect for target [740, 754, and 736 ms for targets 3–5, respectively; F (2,38) = 1.200; *p* = .312] and significant interaction between target and distance [F(4,76) = 3.908; *p* = .006]. We then compared distances −1 and 1 for all targets [target 3: t(19) = 0.760, *p* = .457; target 4: t (19) = −0.910, *p* = .374; target 5: t(19) = −1.012, *p* = .324]. The non-significant results make the assumption highly unlikely that the activation strength was asymmetrical.

Since the seven levels of target–prime distance contain varying numbers of observations (see Fig. 4), we opted to further investigate the impact of target–prime distance by means of a regression analysis.

A comparison of the regression coefficients revealed a significant difference between the V-function and the step-function for Braille. V-shape predictor — mean β = 6.72, MSE = 1.84. Step predictor — mean β = −1.53, MSE = 1.94, t(19) = 2.827, *p* = .011. However, no significant difference was found for the visual number words. V-shape predictor — mean β = 1.35, MSE = 1.66. Step predictor — mean β = 2.35 MSE = 1.97, t(19) = −0.339, *p* = .739. The assumption of collinearity was not violated (all distances: target predictor VIF = 1.138, V-shape predictor VIF = 1.103. step-shape predictor VIF = 1.241). We also tested whether the V-function predictors differed significantly from zero. These analysis showed a significant difference for the V-function predictor when compared to zero for Braille notation [t(19) = 3.653; *p* = .002] but not for number words [t(19) = 0.814; *p* = .426]. We then removed data point target-prime 0 to further test whether the V-shape curve was determined by identity priming or whether it additionally reflects distance-related priming and thus semantic access (following Roggeman et al., 2007). A comparison of the V-shape predictor with 0 revealed a non-significant difference for Braille (mean β = −1.49, MSE = 2.15, t(19) = −0.691, *p* = .498, 2-tailed) indicating no priming beyond distance −1/1 and thus no semantic access; a significant difference for visual number words (mean β = −4.18, MSE = 1.87, t(19) = −2.236, *p* = .038, 2-tailed) indicating an “inverse” semantic priming. While for Braille we observe an identity priming and no evidence for semantic access, for number words there are two effects: an identity priming with an “inverse” semantic priming. Since priming effects are particularly dependent on stimulus timing, the observed “inverse” semantic priming might directly results from SOA (stimulus-onset asynchrony) used in our design. In line with our a priori predictions, we restricted regression analysis to distances −1 up to 1 (including zero distance) in order to keep the same target–prime distance for each target used in the experiment. This revealed a significant difference between the V-function and step-function for both prime notations [Braille: V-shape predictor — mean β = 27.40, MSE = 6.25; step predictor — mean β = −2.16, MSE = 2.44, t (19) = 4.004, *p* = .001. Number words: V-shape predictor — mean β = 14.11, MSE = 4.24; step predictor — mean β = 1.35 MSE = 2.39, t (19) = 2.347, *p* = .030, Fig. 5C]. The assumption of collinearity was not violated (target predictor VIF = 1.000, V-shape predictor VIF = 1.333. step-shape predictor VIF = 1.333). The V-function predictor was the best predictor for both the Braille and number words notation. We subsequently ran *t*-tests to verify whether the V-function predictors would differ significantly from zero; they revealed a significant difference for V-function predictors of both notations [Braille: t (19) = 4.386, *p* < .001. Number words: t(19) = 3.327, *p* = .004]. Taken together, these results provide quantitative evidence of the difference between the V-shape and step-like priming curves for these two prime notations, with a striking difference between the V-shape and step-like priming curves for Braille. The difference of the V-shape regression coefficients between Braille and number words only marginally failed to reach statistical significance [t(19) = 1.784, *p* = .090].

4. Discussion

The current study revealed three main findings. First, we observed a significant impact of numerical primes in both prime notations, Braille and number words. This priming was best characterized by a V-shaped function in both notations. Further analyses revealed that the observed priming is due to identity priming rather than semantic priming.

Participants were fastest at naming Arabic digits when the prime–target distance was zero (e.g. “three” to “3”), with a symmetrical decrease of activation strength for neighboring numbers (e.g. “two” to “3” or “four” to “3”; Fig. 4) regardless of the prime notation. V-shaped and step-like priming functions are reported for symbolic (e.g. Arabic digits to Arabic digits; Koechlin et al., 1999; Naccache & Dehaene, 2001; Reynvoet et al., 2002) and non-symbolic numerical priming, respectively (Roggeman et al., 2007; Van Opstal, Gevers, De Moor, & Verguts, 2008). Here, we found that the V-function predictor, contrary to the step-like predictor, was the best predictor for Braille notation when performing both regression analyses (including all distances and when restricting them to two). This suggests that Braille numbers allowed direct access to a numerical code rather than resulting in counting up to the ordinal position of the corresponding letter in the alphabet.

We did not observe any evidence for semantic priming beyond a target–prime distance of ± 1; this diverges from earlier results obtained by Roggeman et al. (2007). One major difference between our paradigm and the task used by Roggeman et al. (2007) is the symbolic priming notation. While Roggeman et al. (2007) observed semantic V-shaped priming with Arabic digit primes, we did not observe such a semantic priming using number word primes. This leads to an important question concerning the nature of the activated code. Did prime and/or target numbers in our task activate a semantic number code or did participants engage in a direct conversion of the Arabic number (grapheme) into a phoneme (identity priming)? In our results, we observed a strong effect of repetition priming but no strong evidence for an impact of numerical distance larger than one between prime and target, which would be typical for semantic code activation. Based on the Triple Code Model of number processing (Dehaene & Cohen, 1995), we propose that the mechanism responsible for priming effects in our paradigm is a direct grapheme–phoneme conversion. Under this mechanism, both Braille numbers and number words directly activate a phonological number code which, in turn, was accessed by the Arabic digit target (Fig. 1).

The V-shape coding obtained in our paradigm is most likely driven by identity priming, and is thus different in some aspects from the V-shaped coding described by Roggeman et al. (2007) for Arabic digit primes and targets. In contrast to us, Roggeman et al. (2007) did observe an effect of numerical distance between prime and target; this is suggestive of semantic code activation for Arabic digit primes and targets. This difference suggests that compared to Arabic digits, number words are less prone to automatically activating a semantic number code.

Surprisingly, the repetition priming was marginally stronger for Braille compared to number words. Assuming that the grapheme-–phoneme conversion is more automatized for number words, this finding may be explained by the procedural difference in our paradigm. Since Braille reading in general is more effortful than word reading, we presented Braille primes for 300 ms, while number words were presented for 83 ms only. This difference may be reflected by a slightly more pronounced priming effect for Braille in our experiment.

The different timings for different conditions are inevitably particular to specific modalities of the primes: the tactile, and the visual. For the visual priming to occur, the stimuli have to be presented in a very fast manner. Here, prior to the main experiment we established the shortest interval possible at which subjects could recognize Braille numbers. Then — by adjusting remaining intervals accordingly — we observed a cross-modal priming. In the visual priming paradigms the participants are presented with the mask to avoid an afterimage — a phenomenon unique for the visual stimuli not the tactile ones. It is therefore very unlikely that different intervals used in the two conditions could have had affected the main finding presented here, namely

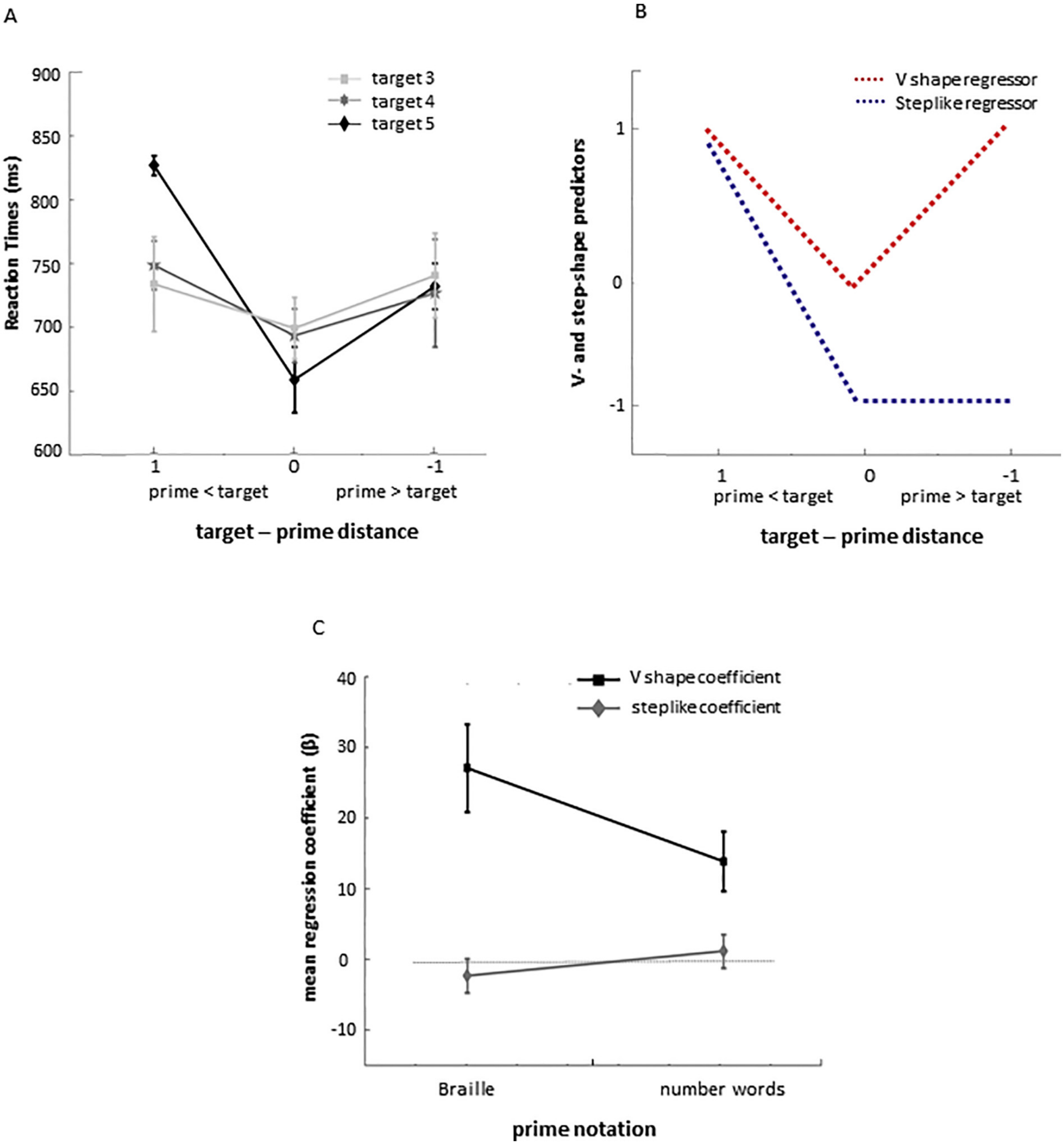

Fig. 5. (A) Single subject data shows RTs for three prime-target distances (1,0,-1) for Braille prime notation. Panel (B) illustrates the regressors for V-shape and steplike. Panel (C) shows mean regression coefficients for the predictors describing step-like and V-shape priming functions as a function of prime notation (for Braille notation and for number words notation). The regression was run for each participant separately. Error bars denotes S.E.M.

the occurrence of the tactile-to-visual number priming.

In our study, we tested sighted people who learned Braille numbers when they were already fluent in recognizing Arabic digits. Such cross-modal number priming is in line with the notion of a generalized magnitude system (Krause et al., 2013; Walsh, 2003). We propose that during Braille acquisition our participants mapped Braille patterns to their internal number representation. This supports the view that the brain processes abstract magnitude information according to a shared code, independent of the modality, which further reveals a direct relationship between tactile and abstract numerosities and the presence of a magnitude code shared by both modalities.

In conclusion, based on our observation of cross-modal priming, best characterized as identity priming, we propose that tactile Braille numbers and number words are place coded. We presume that the observed effects are most likely due to pre-activation of a phonological code and thus, they bypass the mental number line. In our study, we observed V-shape priming pattern for Braille to Arabic digits priming, which may be taken as evidence for place coding of Braille digits. However, we have not observed any semantic access. Therefore, we presume that processing Braille digits can bypass the semantic activation of the mental number line (i.e. they directly prime the target Arabic digit), at least when the prime was identical with the target. Additionally, since there was no semantic access for Braille digits, we presume that the priming effect occurred on the phonological level, i.e. activated a phonological representation mutual for Braille and Arabic digits. In other words, we assume that processing Braille number activated a phonological representation of its corresponding numerosity which, in case of identical numbers, was shared by an Arabic number.

This facilitation effect on the phonological level resulted in the observed identity priming effect. This further signifies that Braille digits and Arabic digits share a code that is phonological rather than semantic. In light of our findings, the Triple Code within the Triple Code Model (Dehaene et al., 1999; Molko et al., 2003) becomes a Quadruple Code, since we have to assume an additional tactile number code for Braille numbers, which might, or might not share some of its representations with the visual and/or the phonological number code (see Siuda-Krzywicka et al., 2016).

Finally, we wish to emphasize that the above conclusions are valid for the particular population we studied. Our subjects were slow readers, with skills roughly equivalent to second grade children. One has to consider the fact that priming is notoriously dependent on stimulus timing, that stimulus timing was, by necessity, slow, and that the subjects processing of Braille digits, while symbolic, was much less practiced than their processing of Arabic digits. To our knowledge, our subjects are the only group of dual tactile-visual readers described so far, and it remains to be proven whether surpassing their skills is achievable. However we cannot exclude the possibility that in an imaginary and ideal population of sighted Braille readers with reading speeds approaching those of the Blind, semantic priming would have been, perhaps, possible.

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Declaration of competing interest

The authors declare no conflicting financial interests.

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