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Reading numbers is harder than reading words: An eye-tracking study

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ABSTRACT

We recorded the eye movements of adults reading aloud short (four digit) and long (eight to 11 digit) Arabic numerals compared to matched-in-length words and pseudowords. We presented each item in isolation, at the center of the screen. Participants read each item aloud at their pace, and then pressed the spacebar to display the next item. Reading accuracy was 99 %. Results showed that adults make 2.5 times more fixations when reading short numerals compared to short words, and up to 7 times more fixations when reading long numerals with respect to long words. Similarly, adults make 3 times more saccades when reading short numerals compared to short words, and up to 9 times more saccades when reading long numerals with respect to long words. Fixation duration and saccade amplitude stay almost the same when reading short numerals with respect to short words. However, fixation duration increases by ~50 ms when reading long numerals (~300 ms) with respect to long words (~250 ms), and saccade amplitude decreases up to 0.83 characters when reading long numerals with respect to long words. The pattern of findings for long numerals—more and shorter saccades as well as more and longer fixations—shows the extent to which reading long Arabic numerals is a cognitively costly task. Within the phonographic writing system, this pattern of eye movements stands for the use of the sublexical print-to-sound correspondence rules. The data highlight that reading large numerals is an unautomatized activity and that Arabic numerals must be converted into their oral form by a step-by-step process even by expert readers.

1. Introduction

Reading Arabic numerals is a skill required in daily life (Lopes-Silva et al., 2014; Meyerhoff et al., 2012). Reading Arabic numerals is also a skill that is commonly assessed when administrating a test to identify the mathematical abilities that are present or impaired among individuals (Cohen et al., 1994; Lafay & Helloin, 2016). Although it is a matter of reading, reading Arabic numerals is nonetheless a fundamentally different activity compared to word reading. Word reading in alphabetic languages follows a phonographic writing system, in which the graphic units mostly represent phonemes (Taylor & Olson, 1995). In such systems, graphic units do not have a meaning on their own but by being assembled with other symbols to form words. Phonographic systems are commonly considered economical in terms of the load they exert on the memory because one only has to learn a relatively small number of graphic units. However, they require good skills in phonological awareness (i.e., the ability to perceive and manipulate the sound components of language) to associate them with the right graphic units. Most of the alphabetic writing systems follow a left-to-right direction of reading. In the writing system underlying Arabic numerals, called *logographic* or *ideographic*, each symbol (or logogram) as a whole stands for a lemma (i.e., has a meaning in itself; Taylor & Olson, 1995). For example, the Chinese character 木 refers to the word "tree" and the digit 1 refers to the quantity or rank 1. Thus, learning to read in a logographic writing system does not involve the ability to perceive sound units smaller than morphemes, but generally requires a large deal of memory because a distinct symbol must be associated with each oral unit in the language. In the case of Arabic numeration, the memory load is not heavy because there are only 10 signs to know (digits from 0 to 9). The capacity to represent the infinity of quantities with only 10 symbols is

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precisely one of the main strengths of this numeration, compared to others such as the Roman one. The main challenge associated with Arabic numeration relies on the fact that to express quantities higher than nine, symbols must be combined between them. Thus, to read Arabic numerals, individuals must match the rules of the verbal number system to the rules of the Arabic code (Lopes-Silva et al., 2014; Moura et al., 2015). The verbal number system is linguistically structured, with a lexicon (four, sixty, hundred, or thousand) and a syntax—a particular word order—that express relations of addition (fifty-six) or of multiplication (seven hundred). The number words in French are similar to the English ones in the sense that they are also organized in lexical classes for units and decades, they also have particulars (e.g., between 11 and 16), and they follow the same word order rules for addition and multiplication relations. Concerning the Arabic code, the syntax or principle that allows the formation of all numbers based on its small lexicon (digits from 0 to 9) is the positional value (or place value): The values of the digits are intertwined with their position in the numerical string by following a power of base 10. For instance, each passage to the superior base-10 value is marked by an additional occupied rank on the left. Thus, learners must grasp that single digit represent units (10^0), the first additional rank to the left indicates the number of tens (10^1), the second additional rank to the left indicates the number of hundreds (10^2), etc. Thus, the size of Arabic numerals increases from right to left (Fuson, 1990), though the oralization of the numerals begins on the left. Therefore, when exposed to large numerals such as 43,829,516, to name the first digits correctly ("forty-three million…"), the reader must determine the number of ranks occupied from the right. Note that Arabic numerals can also be encountered without thousand separators, for instance in different cultures or writing styles. This is often the case for ordinal numbers such as license plates or address numbers.

Despite these theoretical specificities of the Arabic numeral writing system, the mechanisms involved in reading such items and the differences with the reading of phonographic items are not so clear empirically. For example, the literature has shown that difficulty reading numerals is an extension of dyslexia (Cohen et al., 1994) or that reading Arabic numerals is done from left-to-right (Meyerhoff et al., 2012). In fact, the reading mechanisms underlying Arabic numerals are above all much less studied than word reading has been. The acquisition of reading words has been widely studied through behavioral studies. Word reading is typically acquired via two competing routes (the dual route model; Coltheart et al., 2001). In the first, the sublexical route, words are decoded serially using grapheme-to-phoneme correspondence rules to assemble the phonological representations of words (Coltheart et al., 1993). The use of this slow route, in which words are decoded from small unit to small unit, is attested by phenomena such as a word length effect (i.e., time to read a word increases with the number of letters to be processed) and regularization errors (i.e., irregular words, which are words whose pronunciation does not follow a regular grapheme-phoneme correspondence, being read phonologically; Sprenger-Charolles et al., 2003; Ziegler et al., 2014; Ziegler & Goswami, 2005). Young learners strongly rely on this route, whereas adults still mobilize it to read unknown words or pseudowords. In the other route, the lexical one, the spellings of words directly match representations in the orthographic lexicon, resulting in fast activation of the corresponding phonological and semantic representations. Such an ability becomes dominant from grade 3 and it is very widely used by adults (Sprenger-Charolles et al., 2003). Note that proficient readers do not necessarily recognize whole words in one glance nor do they recognize pseudowords grapheme by grapheme, but that for both types of items, sublexical units come into play, such as syllables or morphemes (Álvarez et al., 2000; Burani & Laudanna, 2003).

Although the aforementioned behavioral studies have proven extremely useful in understanding the reading mechanisms, these sources of information have limits in addressing a finer-grained level of information processing (Cop et al., 2015). The measurement of eye movements during reading is of great interest for inferring more precise ongoing processing because such movements reflect the cognitive and linguistic processes at work (Blythe et al., 2009; Ducrot et al., 2013; Engbert et al., 2005; Rayner, 1986). Moreover, eye-tracking is considered the closest experimental parallel to the natural reading process because reading activity while registering eye movements is not confounded by task-related processes required in other tasks (e.g., lexical decision; Cop et al., 2015). In the past four decades, an impressive number of eye-tracking studies have been conducted on reading words, sentences, or texts (Rayner, 2009). It is now well acknowledged that as reading skill increases, saccade length and perceptual span also increase, whereas the number and duration of fixations decrease (Rayner, 1998, 1986). The number of regressions (i.e., eye movements in the direction opposite to normal reading) also decreases with reading expertise, but it still represents 10–15 % of eye movements during text reading among proficient readers (Rayner, 2009). Skilled readers spend more time looking at long than short words (Just & Carpenter, 1980), mainly because refixation probability is higher on longer words (Vitu et al., 1990). Skilled readers also spend more time looking at unpredictable words than they do looking at predictable words (Rayner et al., 2007). Moreover, the perceptual span has been found to be asymmetric according to the reading direction (Rayner, 1998, 1986). More precisely, for English, the span for letter discrimination extends about four letters to the left and about eight to fifteen letters to the right of the fixation point (Rayner, 1998). Thus, the landing position (the initial fixation in a word) tends to be halfway between the middle and the beginning of a word. Eye-tracking studies have also allowed a better understanding of subnormal reading skills. Struggling readers not only show stronger word length effects (Hutzler & Wimmer, 2004) and more refixations (Ducrot et al., 2013; Hawelka et al., 2010) than normal readers do, but also an absence of left-right asymmetry in the perceptual span (Bellocchi et al., 2013; Ducrot et al., 2003). Such observation yielded authors to suggest that dyslexia is associated with a narrower perceptual span and abnormal processing of information outside of foveal vision (Aghababian & Nazir, 2000; Bellocchi et al., 2013).

The mechanisms underlying Arabic numeral reading (i.e., number transcoding) are less studied. Many of the behavioral studies have focused on whether Arabic numerals could or could not be processed without involving a semantic activation (e.g., Brysbaert et al., 2000; Cipolotti & Butterworth, 1995; Cohen et al., 1994; Dehaene, 1992; Fias et al., 2001; McCloskey, 1992). Translingual studies have also investigated whether the phonological codes associated to Arabic numerals were automatically activated (Göbel et al., 2014). It has emerged from these studies that the view of two- or three-digits numerals automatically triggers the corresponding phonological codes among individuals (Göbel et al., 2014; Pixner et al., 2011). It has also emerged that some frequent and relatively short numerals are stored in a lexicon, associated to encyclopedic knowledge and with direct connections to a phonological output lexicon, somewhat similar to the lexical route in word reading. For example, Alameda et al. (2008) showed that number naming and number decisions were faster after an associative prime (e.g., 747 preceded by the word *Boeing*) than they were after an unrelated prime. The few eye-tracking studies conducted on Arabic numeral processing each used a number comparison task and rarely involved numerals larger than two digits (Bahnmueller et al., 2016; Brysbaert, 1995; Huber et al., 2015, 2014; Moeller et al., 2009a, 2009b). They mainly aimed at investigating whether the processing of tens and units was parallel or sequential. Based on reaction time and eye-movements emerging from comparisons of compatible (e.g., $54 < 97$ with tens $5 < 9$ and units $4 < 7$) or incompatible (e.g., $54 < 92$ with tens $5 < 9$ but units $4 > 2$) pairs of numbers, it has been suggested that tens and units are processed in parallel rather than sequentially (Bahnmueller et al., 2016; Moeller et al., 2009a, 2009b). The only study that investigated the eye movement that occurs during comparisons of larger numerals (i.e., 653,281 vs. 654,781, response through keyboard) highlighted that such multidigit numerals are processed in chunks of shorter digit strings, with different chunks being processed sequentially but with digits within these chunks being processed in parallel (Meyerhoff et al., 2012). The study also concluded that sequential processing follows a linear left-to-right exploration of the numbers, guided by the search for the first digit of the numbers to compare that allows one to distinguish them. However, it is likely that such a directional exploration, which is opposite to the right-to-left increasing-quantity orientation of the Arabic numeration described earlier, has been emphasized by the nature of the task used. When having to compare pairs of numbers of the same length, the most relevant strategy is to compare them from the digits expressing the highest quantity (i.e., from the left).

Up to now, although studies have shown that the eye movements that occur in a logographic writing system (e.g., Chinese characters) are different from those that occur in alphabetic systems (Yen et al., 2009), no study has investigated the eye-movements that occur when it comes to reading aloud multi-digit numerals nor has compared such movements to the ones that occur on matched-in-length phonographic items. Given all the information that could be extracted from eye-tracking studies for word reading, investigating the eye movements that take place when reading Arabic numerals would shed new light on the fine-grained level of cognitive processing involved. It could eventually also provide information about the mechanisms at play in the learning phase and help us understand the difficulties that a considerable number of individuals face in that activity (Butterworth & Reigosa, 2007; de Clercq-Quaegebeur et al., 2018; Moll et al., 2014; Moura et al., 2013; Pieters et al., 2012). Therefore, this study aimed to investigate the eye movements of normal-reading adults when reading short and long Arabic numerals (with or without a thousand separators) compared to matched-in-length words and pseudowords. Comparing the eye movements that occur across these different types of items should contribute to identifying the processes involved in the particular logographic system that Arabic numerals comprise, relative to the processes involved in our widespread alphabetic system. Because the short numerals used in this study are composed of a number of digits that can be perceived at a glance (i.e., subitizing), we expected no or little difference in eye movement between short numerals and matched-in-length words and pseudowords. Conversely, we expected important differences across long items. Among the phonographic system, many studies have shown that items that are read by conversion rules (i.e., pseudowords relative to words or items read by beginning or struggling readers relative to expert readers) give rise to more and shorter saccades as well as to more and longer fixations (De Luca et al., 2002; Rayner, 1986). Thus, because most of numerals have to be read by converting the digits of the Arabic code into their oral form according to their positional value (Lopes-Silva et al., 2014; Moura et al., 2015)—and not by matching a phonological representation stored in a mental lexicon to a certain pattern of digits—we expected more and shorter saccades as well as more and longer fixations on long numerals compared to matched-in-length words and pseudowords. This was expected to be even more the case for numerals without thousand separators, in which chunks of three digits are not highlighted. It should be noted that fixation number and saccade number are generally redundant measures (each fixation is followed by a saccade and vice versa), and in non-reading tasks, saccade amplitude and fixation duration are related in some way (Rayner, 1998; Unema et al., 2007). However, saccade amplitude and fixation duration do not correlate during reading, suggesting that language processing eliminates the relationship (Rayner, 1998). Because the relationship between fixation and saccade measures depends on the nature of the tasks, and since eye-movements occurring when reading aloud large numerals have not yet been studied, we report the parameters of both in the current study. Both have been shown to vary with text difficulty during reading (De Luca et al., 2002; Rayner, 1998, 2009), and it is possible that they are neither correlated nor redundant.

2. Materials and methods

2.1. Participants

Participants were 36 students in psychology from the University of Lausanne (27 women and nine men; mean age = 21.3 years old; SD = 4.15). Their native language was French, and they had normal or corrected-by-lenses vision and no history of learning disorders. To take part in the study, they received 2 points to validate a methodology course as well as a 15 CHF (14 euros) voucher for a bookshop.

2.2. Tasks and materials

Participants were asked to read 96 items in total, in a single session lasting approximately 10 min. The Arabic numerals were 12 short numerals with separators, 12 short numerals without separators, 12 long numerals with separators, and 12 long numerals without separators (Table 1). The short numerals consisted of four digits because individuals can perceive up to four items at a single glance (i.e., subitizing; Starkey & Cooper, 1995). No shorter numeral was included to maintain the "with or without separators" condition. The long numerals were composed of eight to 11 digits, corresponding to the dozens of millions up to the dozens of billions. Varying the length of the long items was necessary to prevent participants from anticipating the order of magnitude of the numerals they had to read. Numerals were controlled for parity and magnitude (see supplementary material "data_saccades.xlsx", column D). The words and pseudowords were matched in length to the numerals, resulting in 12 short words and 12 short pseudowords (of four letters) and 12 long words and 12 long pseudowords (of eight to 11 letters; for similar differences between short and long words, see Joseph et al., 2009). The words were frequent French words of different orthographic regularity (two-thirds regular words and one-third irregular words) and of different grammatical natures (eight nouns, eight verbs, four adjectives, and four adverbs in total). The pseudowords were matched to the words in terms of number and structure of syllables while avoiding phonological and orthographic neighbors (Table 1). The items were presented at the center of the screen in 40-point Verdana font (see supplementary material, "stimuli examples.zip").

Each trial included the sequential presentation of a target item and a blank screen displayed on a gray screen background and was preceded

Table 1
Stimuli. See the supplementary materials for examples of on-screen appearance.

	Words	Pseudowords	Numerals with separators	Numerals without separators
Short	amer	érul	1′549	1293
	aula	fabu	2′391	1362
	brut	inor	2′497	2638
	déjà	iqué	3′165	3127
	écho	isan	3′618	3748
	être	muar	4′976	4579
	fuir	oufé	5′482	5862
	iris	spac	6′578	6124
	saga	stau	6′814	6925
	très	udre	7′849	7524
	unir	ujar	8′743	8597
	user	zago	9′736	9351
Long	astucieux	birtajicer	19′582′743	24739165
	baptiser	carriloge	2′137′954′867	57468391
	boulangerie	daurinfarue	23′914′856′297	76951238
	caoutchouc	frinchar	327′569′184	175928346
	carrelage	lomanube	39′681′742′538	624731958
	dorénavant	ostéciant	43′829′516	938426157
	franchir	outigieux	536′287′419	3158963472
	fréquemment	pannesquier	6′178′249′358	4863167295
	impatient	pondaser	7′849′125′463	8627514359
	limonade	pouitcheau	82′745′961′354	16259874317
	participer	quimmévrant	857′491′326	37862951462
	questionner	tulanévont	97′483′261	97654328164

by a drift check, during which the experimenter made sure the participant centered their gaze within a black circle of diameter 0.48° and then validated the beginning of the trial. The target item was presented on the screen until the participant produced an oral response and pressed the keyboard's space bar (Fig. 1). Immediately following the response, the blank screen was presented for 100 ms, followed by the drift check indicating the beginning of the next trial. The target items were presented to the participants in two blocks of trials. One block consisted of the presentation of 48 randomly presented numeral trials, and the other block consisted of the presentation of 24 randomly presented word trials followed by 24 randomly presented pseudoword trials. The order of the two blocks was counterbalanced across participants. Before each item category, participants were instructed to read the items aloud as accurately and as fast as possible. For the pseudoword category, it was specified that the items had no meaning. Three training trials preceded the experimental phase for each category of items, during which feedback was provided by the experimenter.

2.3. Procedure

This experiment was approved by the ethical committee of the University of Lausanne (reference of decision: C_SSP_022021_00006). Participants were individually installed in a quiet, dimly lit, room, sitting 930 mm from the computer screen. The items were presented on a 24-inch LCD monitor (visible screen width and height: 520 × 325 mm) with a resolution of 1920 × 1200 with a refresh rate of 60 Hz. A chin and forehead rest ensured a correct head position throughout the entire experimental procedure. Ocular dominance was detected with the "hole-in-card" test by using the participants' hands and centered gaze. The dominant eye-gaze position was recorded at a sampling frequency of 1000 Hz with a desktop-mounted EyeLink 1000 with 35-mm aperture lenses (SR Research Ltd., ON, Canada), placed at 530 mm distance in front of the participant. With this experimental setup, a 100-mm long and 7-mm high word, pseudoword, or numeral was displayed centered on the screen that corresponded to a horizontal and vertical visual angle of 6.11° and 0.43°, respectively. The eye tracker camera was focused on participants' eyes by rotating the lens-focusing ring until the eye image was clear, with the pupil centered when the subject looked at the center of the screen. The pupil and corneal reflection thresholds were defined by selecting the auto-thresholding option available in the EyeLink software and accepting it if the pupil threshold ranged between 75 and 110, and the corneal threshold was below 230. Illumination output was increased or decreased if pupil threshold was too low or pupil and corneal thresholds were too high, respectively. Before running the experimental task, a 9-point automatic calibration and validation was used and repeated until the maximum and average validation offset was <1° and 0.5°, respectively.

2.4. Software

The experiment was programmed using the Experiment Builder software. Data were processed and were exported using the Data Viewer data analysis software. Statistical analysis was performed with MATLAB.

2.5. Outcomes

2.5.1. Behavioral variables

We recorded accuracy of response (coded as 0 and 1 for incorrect and correct responses, respectively) for each item presented to each participant.

2.5.2. Eye-tracking variables

Fixations and saccades were identified by the eye tracker in real-time based on an internal heuristic saccade detector (SR Research, 2018). Saccades were defined using a velocity threshold of 35°/s and an acceleration threshold of $9500°/s^2$. We used the starting and ending positions of saccades on the screen (horizontal and vertical coordinates in pixels) to determine their direction (towards the left or the right). The EyeLink detects blinks as "saccades containing a blink" (SR Research, 2018): We excluded these events from all analyses. Immediately before each stimulus, a drift check consisted of fixating a black circle in the center of the screen, at exactly the same location where the stimulus would subsequently show up (see Fig. 1). When the experimenter pressed the button to allow the stimulus (e.g., a word) display, the participant was already fixated on the center of the screen; Visual inspection revealed this often (though not always) caused a leftward saccade to reposition the gaze towards word start. Hence, we systematically removed the first saccade of each trial from analysis. The pattern of results does not change when including the first saccade of each trial.

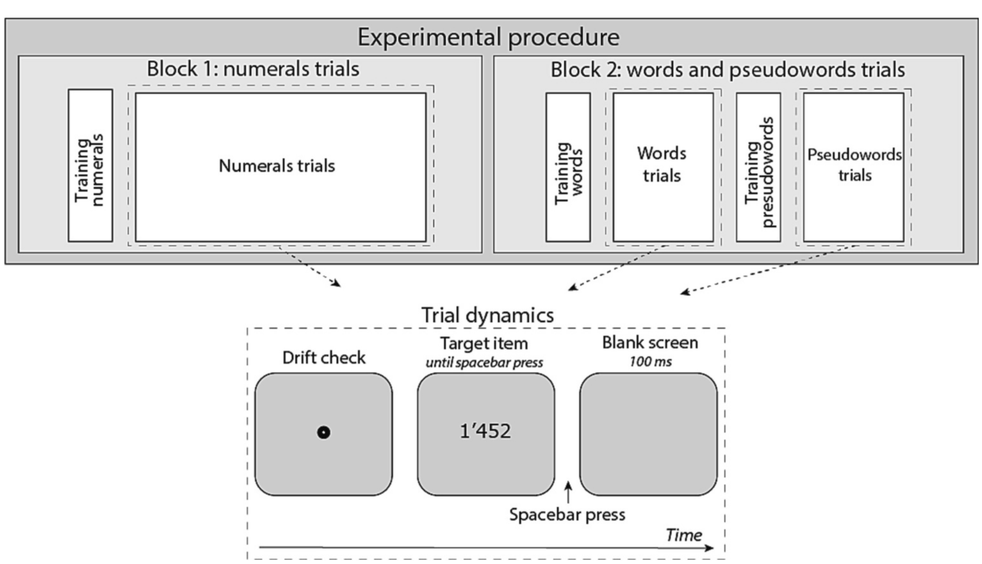

Fig. 1. Experimental procedure and trial dynamics. The order of presentation of the two blocks and the choice of target item were chosen for simple representative purposes. The presentation of the blocks was counterbalanced across participants, as well as the content of the target item changes according to whether it belonged to a numeral, word, or pseudoword trial.

2.6. Data analysis

The experimental conditions corresponded to the class of items that were randomly presented to participants for reading: Words, pseudowords, numerals with separators, and numerals without separators. Thirty-six participants read 96 items, totaling 3456 trials. We used violin plots to describe the distribution of the results across experimental conditions. We described central tendencies and dispersions of the data through medians and interquartile ranges (IQRs) given nonnormal distributions. Histograms (frequency distribution plots) are provided in the supplementary material ("Regression Models.pdf"). Regarding inferential statistics, we applied generalized linear mixed regression models to consider the hierarchical organization of the results (saccades/fixations nested in items nested in participants) and the nonnormal distributions. We built four models, one for each variable of interest: Fixation number, saccade number, fixation duration, and saccade amplitude. The modeling distribution was the gamma distribution with log link. See the supplementary material ("Regression Models.pdf") for the assessment of the gamma distribution with the sample distribution. The sample size of fixation duration and saccade amplitude varied because the number of fixations and saccades for reading a word varies between people. The model included only intercept factors (participant and trials). The significance level for computing confidence intervals and interpreting results was set to $\alpha = 0.01$. Full model outputs, including fixed and random effects, can be found in the supplementary material ("Regression Models.pdf"). The estimated fixed effects were added to the violin plots.

3. Results

Tables 2 and 3 contain descriptive statistics and regression models respectively.

3.1. Accuracy

In total, 35 items out of 3456 were incorrectly read (i.e., 1 % of the trials). Most of these mistakes occurred on long numerals without separators ($n = 19$), followed by long pseudowords ($n = 9$), long words ($n = 4$), and long numerals with separators ($n = 3$). We included all items in the analyses because mistakes were rare.

3.2. Fixation number

The generalized linear mixed model showed a significant fixed effect of Length ($p < .001$) and Type (all $ps < .001$), indicating that fixation number globally increased from short to long items and from words to numerals without separators (passing through pseudowords and numerals with separators). The generalized linear mixed model also showed a significant interaction of Length × Type (all $ps < .001$; see supplemental material, "Regression Models.pdf") indicating that the increase in fixation number between the different types of items was not the same for short and long items. Fixation number increased much more for long items than it did for short items (Fig. 2). Participants made 2.5 times more fixations when reading short numerals (with or without separators, median = 5) compared to short words (median = 2), and 1.67 more compared to short pseudowords (median = 3). Yet, they made 5 times more fixations when reading long numerals with separators (median = 15) compared to long words (median = 3), and 2.5 compared to long pseudowords (median = 6). The effect of adding a digit separator is visible for long items: Participants made 7 times more fixations when reading long numerals without separators (median = 21) with respect to long words (median = 3), and 3.5 with respect to long pseudowords (median = 6; Fig. 2).

3.3. Saccade number

Saccade number exhibited the same pattern as fixation number. The generalized linear mixed model showed a significand fixed effect of Length ($p < .001$) and Type (all $ps < .001$), indicating that saccade number globally increased from short to long items and from words to numerals without separators (passing through pseudowords and numerals with separators). The generalized linear mixed model also showed a significant interaction of Length × Type (all $ps < .001$; see supplementary material, "Regression Models.pdf"), indicating that the increase of fixation number between the different types of items was not the same for short and long items. Saccade number increased much more for long items compared to short items (Fig. 3). Participants made 3 times more saccades when reading short numerals (with or without separators, median = 3) with respect to short words and pseudowords (median = 1). Yet, they made 5.5 times more saccades when reading long numerals with separators (median = 11) compared to long words (median = 2), and 2.75 times more with respect to long pseudowords (median = 4). The effect of adding a digit separator is visible for long items: Participants made 9 times more saccades when reading long numerals without separators (median = 18) with respect to long words (median = 2), and 4.5 times more with respect to long pseudowords (median = 4; Fig. 3). The fact that some items were read without any saccades is explained by our stimulus display procedure (see Section 2.5.2): When the experimenter pressed the button to allow the stimulus (e.g., a word) display, the participant was already fixated on the center of the screen; hence, they did not need to make saccades in some cases,

Table 2
Descriptive statistics.

		Short items (4 letters/digits)			Long items (8–11 letters/digits)		
		N	Median	IQR	N	Median	IQR
Fixation number	Words	432	2	2	432	3	1.5
	Pseudowords	432	3	2	432	6	4
	Numerals w. separators	432	5	3	432	15	6
	Numerals w/o separators	432	5	2	432	21	12
Saccade number	Words	328	1	0	417	2	2
	Pseudowords	374	1	1	432	4	3
	Numerals w. separators	429	3	3	432	11	5
	Numerals w/o separators	427	3	2	432	18	11
Fixation duration (ms)	Words	943	334	372.75	1561	256	219
	Pseudowords	1192	312.5	313.5	2611	246	171
	Numerals w. separators	2330	292	270	6699	293	244
	Numerals w/o separators	2191	321	303	11,036	302	224
Saccade amplitude (°)	Words	463	0.56	0.41	958	1.07	0.78
	Pseudowords	657	0.59	0.41	1988	0.91	0.64
	Numerals w. separators	1434	0.68	0.44	5208	0.83	0.81
	Numerals w/o separators	1325	0.61	0.3925	9265	0.71	0.53

Note. IQR = interquartile range.

Table 3
Generalized linear mixed regression models.

		Fixation number			Saccade number			Fixation duration			Saccade amplitude		
		Coef. estimate	SE	t	Coef. estimate	SE	t	Coef. estimate	SE	t	Coef. estimate	SE	t
Type	Intercept (words/short items)	0.71*	0.06	11.64	0.24*	0.06	3.78	6.03*	0.04	162.46	−0.44*	0.05	−8.33
	Pseudowords	0.24*	0.04	6.62	0.22*	0.04	5.33	−0.06	0.03	−2.16	0.04	0.06	0.74
	Numerals w. separators	0.94*	0.04	20.99	0.90*	0.05	17	−0.12*	0.02	−4.97	0.22*	0.05	4.34
	Numerals w/o separators	0.89*	0.05	17.55	0.84*	0.06	14.81	−0.08*	0.02	−3.20	0.13*	0.05	2.66
Length	Long items	0.52*	0.03	20.38	0.51*	0.03	15.51	−0.31*	0.03	−11.94	0.60*	0.05	11.39
Interactions	Pseudowords × long items	0.28*	0.04	7.81	0.49*	0.05	10.98	−0.04	0.03	−1.05	−0.11	0.07	−1.67
	Numerals w. separators × long items	0.55*	0.04	15.13	0.83*	0.04	18.66	0.27*	0.03	9.07	−0.25*	0.06	−4.26
	Numerals w/o separators × long items	1.08*	0.04	29.84	1.45*	0.04	32.63	0.24*	0.03	7.87	−0.32*	0.06	−5.37

Note. Coef. Estimates are regression coefficients (*beta*). Asterisks indicate significance at $\alpha = 0.01$. See the supplementary material ("Regression Models.pdf") for 99 % confidence intervals, degrees of freedom and *p*-values.

especially for short items.

3.4. Fixation duration

The generalized linear mixed model showed a significand fixed effect of length ($p < .001$), indicating that fixation duration globally decreased from short to long items. The generalized linear mixed model also showed a significant interaction of Length × Type (all *ps* $< .001$; see supplemental material, "Regression Models.pdf") indicating that the effect of length was not the same for the different types of items. The interaction is highlighted by the fact that fixation duration decreased for long words (median = 256 ms) compared to short words (median = 334), whereas fixation duration stayed the same between long and short numerals (Fig. 4). Moreover, in line with our initial hypothesis, median fixation duration increased by ~50 ms ($p < .001$) for long numerals (~300 ms) with respect to long words and pseudowords (~250 ms). Concerning short items, the median duration of fixations did not increase between words (median = 334 ms), pseudowords (median = 312 ms), numerals with separators (median = 292 ms), and numerals without separators (median = 321 ms). Fixation duration significantly

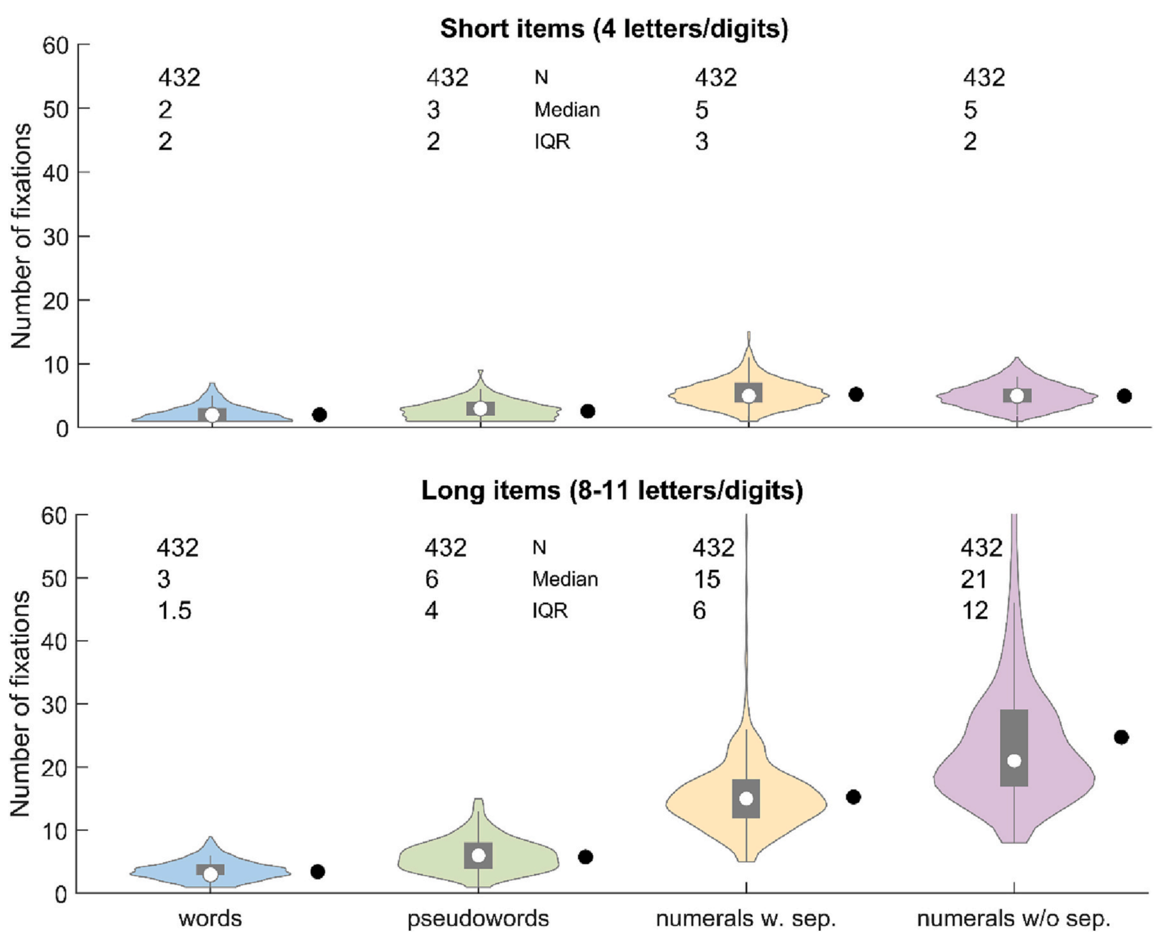

Fig. 2. Fixation number. Violin plots depict the distribution of raw data. Black dots are values predicted by the generalized linear model. Short items are words and numerals of four letters or digits. Long items are words and numerals of eight to 11 letters or digits. $N = 3456$ trials (96 trials × 36 participants). IQR = interquartile range.

decreased by 12 % for short numerals with separators (median = 292 ms) with respect to short words (median = 334 ms, $p < .001$).

3.5. Saccade amplitude

The generalized linear mixed model showed a significand fixed effect of length ($p < .001$), indicating that saccade amplitude globally increased from short to long items. The generalized linear mixed model also showed a significant interaction of Length × Type (all $ps < .001$; see supplemental material, "Regression Models.pdf"), indicating that the effect of length was not the same for the different types of items. The effect of length was stronger for words (81 % increase, from 0.56° to 1.07°) and pseudowords (61 % increase, from 0.59° to 0.91°), and weaker for numerals with separators (39 % increase, from 0.68° to 0.83°) and for numerals without separators (30 % increase, from 0.61° to 0.71°; Fig. 5). As a reference, in our setup, one letter (or digit) spanned 0.43° horizontally (see Section 2.3).

Moreover, in line with our initial hypothesis, median saccade amplitude decreased for long numerals with separators with respect to long words (0.83° vs. 1.07°, $p < .001$) as well as for long numerals without separators with respect to long words (0.71° vs. 1.07°, $p < .001$). Conversely, regarding short items, saccade amplitude stayed almost the same between words (median = 0.56°), pseudowords (median = 0.59°), numerals with separators (median = 0.68°) and numerals without separators (median = 0.61°; see Fig. 5). Saccade amplitude significantly increased by 24 % only for short numerals with separators with respect to short words (0.68° vs 0.56°, $p < .001$).

4. Discussion

This study aimed to investigate the eye movements generated by the activity of reading aloud short and long Arabic numerals presented with or without thousand separators compared to matched-in-length words and pseudowords. Our findings globally showed that in line with our hypothesis, numerals generated more fixations and more saccades than words and pseudowords did, even more so for long numerals and even more without thousand separators. Fixation duration increased by ~50 ms for long numerals (~300 ms) with respect to long words and pseudowords (~250 ms), whereas it did not change while reading short items. Along the same lines, saccade amplitude did not move within short items, whereas it decreased for long numerals (especially those without separators) with respect to long words and pseudowords. It should be noted that part of these results is explained by the timing of number utterances. In fact, it is well known that fixations and saccades are more numerous and fixations are longer in oral reading than in silent reading (Krieber et al., 2017) and that this is because, as the eyes move faster than the reader can produce the words, they generally stay in place longer and move more in place so as not to get too far ahead of the voice (Rayner, 2009). Numbers are longer to pronounce than words and pseudowords of corresponding length, given their logographic nature. However, the number of fixations and saccades is not entirely explained by differences in pronunciation time, since differences in the number of fixations and saccades are not proportional to differences in the number of syllables-a common unit of measurement of articulation rate (Darling-White & Banks, 2021). In fact, short numbers globally contain 4 times as

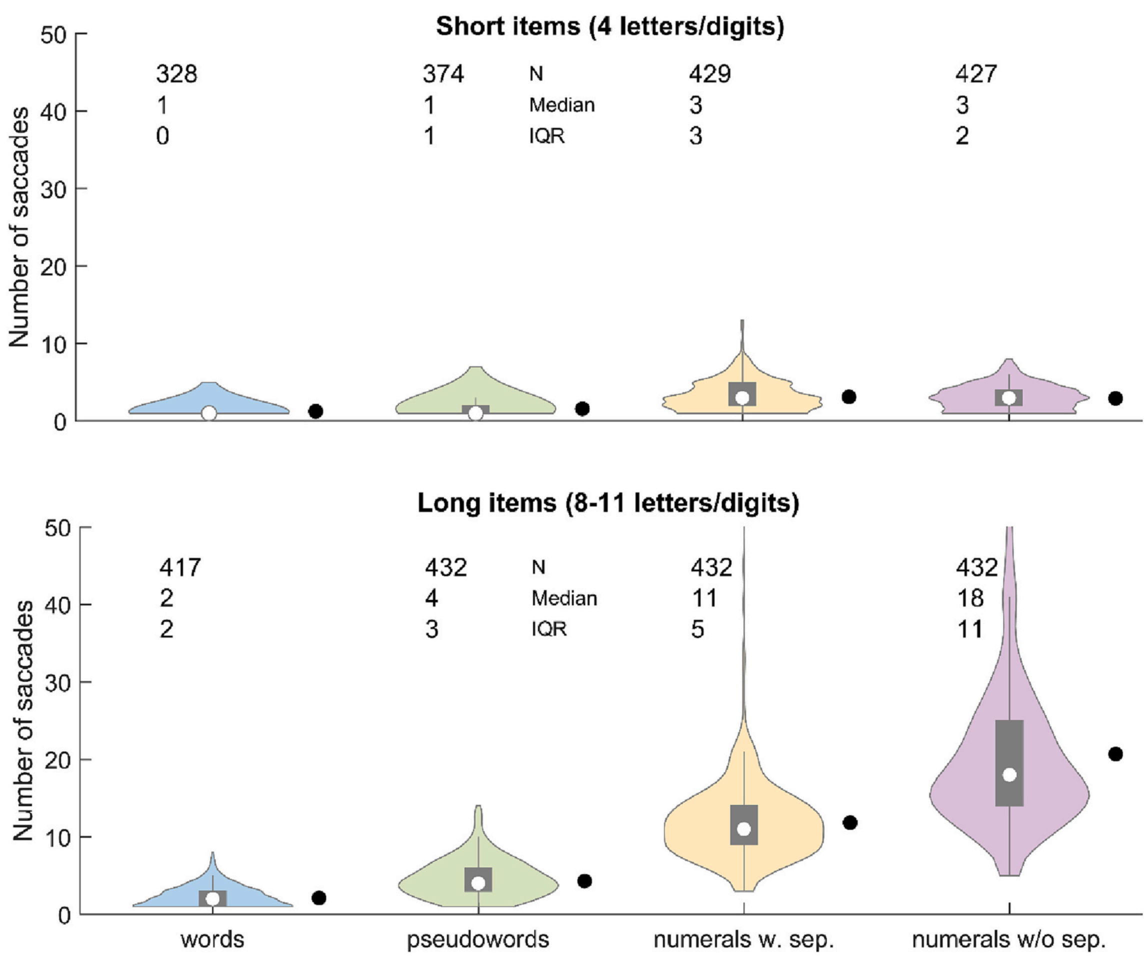

Fig. 3. Saccade number. Violin plots depict the distribution of raw data. Black dots are values predicted by the generalized linear model. Short items are words and numerals of four letters or digits. Long items are words and numerals of eight to 11 letters or digits. $N = 3271$ trials (96 trials × 36 participants, though in some trials participants could read items without making saccades). IQR = interquartile range.

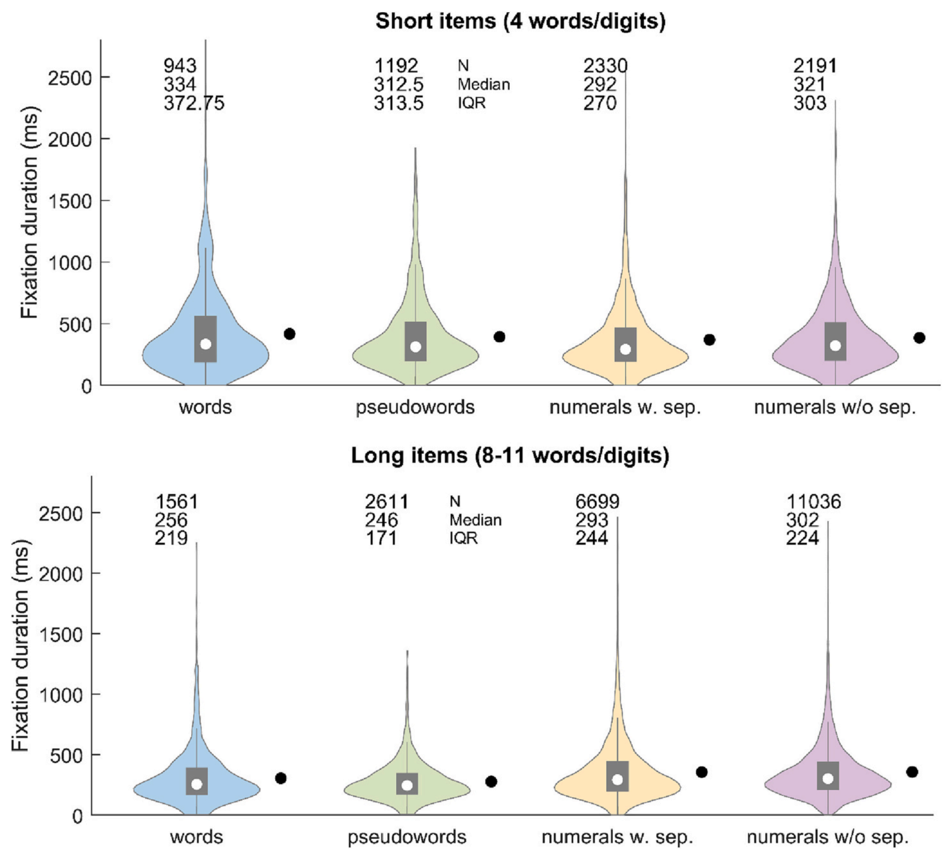

Fig. 4. Fixation duration. Violin plots depict the distribution of raw data. Black dots are values predicted by the generalized linear model. Short items are words and numerals of four letters or digits. Long items are words and numerals of eight to 11 letters or digits. $N = 28{,}563$ (96 trials × 36 participants × all fixations that occurred). IQR = interquartile range.

many syllables as short words and pseudo-words, while generating 2.5 times as many fixations and 3 times as many saccades. In contrast, long numbers globally contain 6 times more syllables than long words and pseudowords, while generating 7 times more fixations and 9 times more saccades. Therefore, the pattern of findings regarding long numerals (i.e., more and shorter saccades as well as more and longer fixations) also shows the extent to which reading long Arabic numerals (e.g., numerals from eight to 11 digits) is a cognitively costly task. Indeed, such eye movements are precisely the pattern of observations made—for phonographic items—among young learners compared to expert readers (Rayner, 2009, 1986), among struggling readers compared to skilled readers (De Luca et al., 2002; Hawelka et al., 2010; Prado et al., 2007), and when reading pseudowords relative to words (De Luca et al., 2002). In this regard, such a pattern of eye movements is commonly interpreted as reflecting the high attentional resources required by the ongoing reading activity. Within the phonographic writing system, this pattern of eye movements stands for the use of the sublexical print-to-sound correspondence rules (Coltheart et al., 2001; Sprenger-Charolles et al., 2003; Ziegler et al., 2014). By showing that among expert readers, reading long Arabic numerals globally generates more and shorter saccades as well as more and longer fixations relative to matched-in-length words and pseudowords, our study highlights that reading large numerals is an unautomatized activity and that Arabic numerals have to be converted into their oral form in a step-by-step process. This cognitive cost is more evident for long numerals without separators. This outcome shows that thousand separators are helpful in reading numerals. Indeed, they make it easier to identify the packs of three digits and thereby the order of magnitude of the numerals to be read. However, and of particular interest, long numerals with separators are still considerably more laborious to read than are matched-in-length pseudowords, which are not stored in any mental lexicon and thereby have to be read using grapheme-to-phoneme correspondence rules (Coltheart et al., 2001). Regarding the number of saccades and fixations more specifically, it should be noted that a larger dispersion (interquartile range) of the data across participants was observed when they read long numerals compared to matched-in-length words and pseudowords. This indicates that individuals have highly variable degrees of ease with the activity of reading aloud long numerals compared to long words, for which the interindividual variability could be reduced by the familiarity of the task. Conversely, and as expected, the results regarding short numerals (e.g., numerals of four digits) highlight the relative fluency with which such numerals are read. They also induce more saccades and fixations than matched-in-length words and pseudowords do, but to a much lesser extent than long items do. The four-digit length of the short numerals was chosen with reference to the subitizing range; that is, the ability of individuals to perceive up to four items in a glance (Kaufman & Lord, 1949; Leibovich-Raveh et al., 2018). Hence, it appears that the subitizing range also applies to transcoding activity. Still, because it has been shown that individuals with mathematic learning disabilities exhibit lower skills in subitizing tasks (Ashkenazi et al., 2013; Schleifer & Landerl, 2011), it could be that four-digit numerals would be read with less ease by individuals facing such difficulties.

Some limitations of the current study need to be pointed out. First, we recorded eye movements on items presented in isolation. Eye movements are not the same when items are presented within sentences or texts (Vitu et al., 1990), and future studies could investigate eye movements when reading numbers in such contexts. Second, by asking participants to read the items aloud, it was not possible to control for differences in pronunciation time of items of corresponding length. In fact, phonographic and logographic items can by nature be matched either in length or in pronunciation time. The read aloud task was chosen to force participants to explore numbers as they must be when

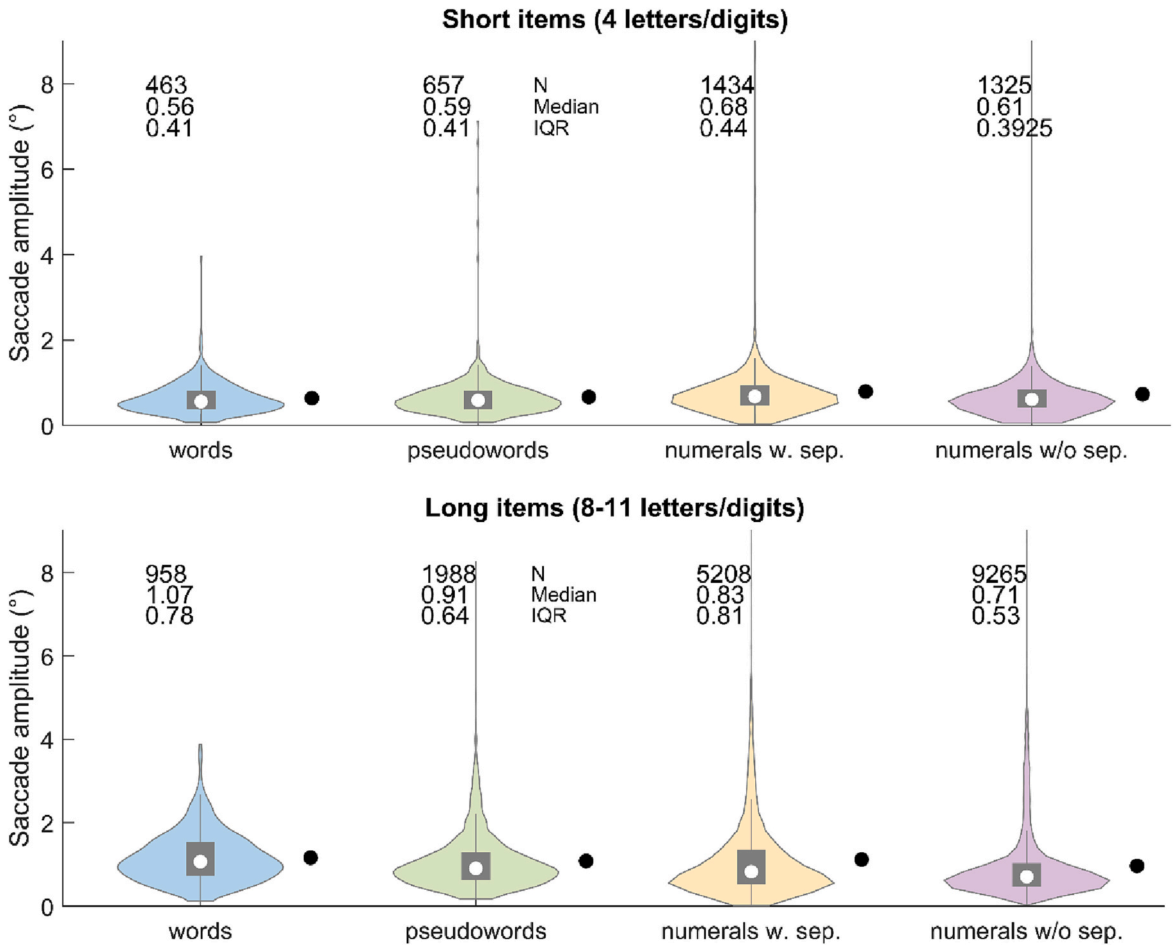

Fig. 5. Saccade amplitude. Violin plots depict the distribution of raw data. Black dots are values predicted by the generalized linear model. Short items are words and numerals of four letters or digits. Long items are words and numerals of eight to 11 letters or digits. $N = 21{,}298$ (96 trials × 36 participants × all saccades that occurred). IQR = interquartile range.

reading them, as a silent comparison task might elicit different mechanisms of number exploration (Meyerhoff et al., 2012). Further studies could investigate eye movements when numbers are to be read versus words matched by number of syllables.

5. Conclusion

This study was the first to measure the eye movements of skilled readers reading aloud short and long Arabic numerals compared to matched-in-length words and pseudowords. It highlighted the extent to which reading long numerals is an unautomatized and congnitively costly activity. Indeed, the long numerals that were the easiest to read (those with thousand separators) were more laborious to read than long pseudowords were (see Supplementary material, “eye tracking example for 4 stimuli.mp4”). Relatively, short numerals were read much more fluently. The information that could be extracted from this experiment among adults opens new perspectives of research. Further studies could investigate the eye movements children generate while reading numerals (i.e., in the acquisition phase) or of individuals facing mathematical or reading difficulties.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2023.103942.

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CRediT authorship contribution statement

Anne-Françoise de Chambrier: Conceptualization, Methodology, Investigation, Writing – original draft, Supervision. **Marco Pedrotti:** Conceptualization, Methodology, Validation, Data curation, Writing – original draft, Visualization, Supervision. **Paolo Ruggeri:** Software, Validation, Investigation, Data curation, Writing – original draft. **Jasinta Dewi:** Investigation, Writing – review & editing. **Myrto Atzemian:** Investigation, Writing – review & editing. **Catherine Thevenot:** Resources, Supervision, Writing – review & editing. **Catherine Martinet:** Conceptualization, Supervision, Writing – review & editing. **Philippe Terrier:** Data curation, Methodology, Validation, Formal analysis, Writing – original draft, Visualization.

Declaration of competing interest

None.

Data availabilityThe data presented in this study are included in the supplementary material ("data_fixations.xlsx", "data_saccades.xlsx", "data_reaction_time.xlsx"), further inquiries can be directed to the corresponding author.

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