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Eye movements when reading Arabic numbers in sentences

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A R T I C L E I N F O

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A B S T R A C T

We examined eye movements in 49 adults as they read aloud or silently rounded and non-rounded Arabic numbers embedded in texts. We compared the patterns of eye movements to those obtained when participants read words and pseudowords matched in length to the numbers. The results revealed that non-rounded numbers elicited more fixations, longer fixation durations, and an increased number of saccades with shorter amplitudes compared to words, with pseudowords and rounded numbers falling in between. This reflects the cognitively demanding step-by-step processing required for number reading. However, this effect was moderated for non-rounded numbers in silent reading, suggesting that without oralization requirement, participants engaged in a more superficial reading. This interpretation was further supported by a higher error rate on a comprehension task administered after reading when the questions were related to the magnitude of the numbers read. Additionally, participants made more leftward saccades when reading numbers compared to words and pseudowords, indicating that despite numbers being oralized from left to right, they must be, to some extent, scanned from right to left to determine the value and therefore the denomination of the various digits. These findings shed light on the cognitive mechanisms underlying number reading.

1. Introduction

Nowadays, Arabic numerals are the most widely used numbering system in the world (Poepsel et al., 2024). This numeration system enables the representation of infinite quantities using just 10 symbols, made possible by its base-10 positional value system. In this system, when a grouping of 10 is reached (10^1, 10^2, 10^3…), a new digit is added to the left. In other words, the units are placed on the right, the tens to their left, the hundreds still further left, and so on, each rank being worth ten times the one before (Ifrah, 2000). This right-to-left orientation originates from Arabic mathematicians who popularized the system, as their script is read from right to left. Languages like Arabic, Hebrew, Urdu, and Persian were historically inscribed on stone with tools such as chisels and hammers. The chisel was held in the left hand and the hammer in the right, allowing the engraver to see the precedent letter and ensure consistent sizing. Interestingly, in classical Arabic, numbers were not only written from right to left but also spoken that way, starting with the least significant digit (Boucenna, 2003). Today, although the values of the respective digits are still determined from right to left, most people read numbers from left to right (Shaki et al., 2009). Concretely, reading the number 5,342,690 involves both recognizing the lexical identity of each digit (5 = five, 3 = three…) and syntactically determining their value by identifying their positional rank from the right (five million, three hundred forty-two thousand…).

If reading numbers requires analyzing sequences of symbols, as does reading words, it is quite clear that they involve different mechanisms. Indeed, double dissociations have been observed in the field of neuropsychology, i.e., brain-damaged patients who had difficulty reading words but were able to read numbers (Cohen & Dehaene, 1995), and vice versa (Dotan & Friedmann, 2019). The dual-route model (Coltheart et al., 2001) is the theoretical frame of reference for word reading. According to it, words can be read through two different procedures, both beginning by the visual analysis of the string of letters. Then, within the sublexical phonological procedure, small written units (letters,

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graphemes, syllables) are converted into their phonological correspondents. This first procedure is very predominantly used at the beginning of learning to read and is still used by expert readers to read words they have not yet encountered. In the lexical procedure, orthographic representations of words are recognized as a whole and linked to their oral form and meaning stored in the internal lexicon. This procedure becomes dominant from the middle of elementary school onwards and is used overwhelmingly by expert readers.

Work on reading numbers is much rarer but Dotan and Friedmann (2018, 2019) proposed a cognitive model to describe the fine-grained processes involved in that activity, built on earlier work and on specific error patterns. This model assumes that numbers are read in two stages involving both different processes. First, at the visual analyzer of digit strings stage, digit identity and digit order are on the one hand encoded. On the other hand, the decimal structure is parallelly extracted by another set of numeric-visual analysis sub-processes: the number of digits, the positions of 0, and the grouping of digits into triplets. Secondly, in the verbal production of number words stage, a number word frame is generated. The model assumes that some of the sub-processes within verbal production are language-dependent, whereas other sub-processes are language-general. The authors also specify that the model focuses on how visually-presented digit strings are read aloud and that the way numbers are understood is another question.

Eye movements have been extensively studied in word/text reading because they are powerful indicators of the fine-grained psycholinguistic mechanisms at work in the reading activity (Cop et al., 2015). In particular, eye movement control models, the main ones being E-Z Reader and SWIFT, focus on how word and text characteristics influence fixation durations and saccade triggering in order to infer the linguistic and cognitive processes at work during reading. While both models start from this premise, they diverge in their conception of lexical processing. The E-Z Reader model posits serial word processing, in which recognition of the current word triggers the programming of the next saccade, while the SWIFT model proposes a parallel and distributed model, in which several words are processed simultaneously at varying degrees of activation.

In a recent study, we applied the eye tracking technique to the study of the mechanisms involved in reading Arabic numerals. The eye movements of adults reading isolated long (8 to 11 digits) and short (4 digits) numerals were compared to the ones occurring on matched in length words and pseudo-words (de Chambrier et al., 2023; Pedrotti et al., 2023). It highlighted that Arabic numerals lead to a more step-by-step conversion process, in contrast to the automatic recognition of words. Indeed, participants made 5 times more fixations and 5.5 times more saccades on long numerals compared to long words, and made 2.5 times more fixations and 3 times more saccades on long numerals compared to long pseudowords. Fixations were also longer, and saccade amplitude shorter when reading long Arabic numerals compared to words and pseudowords. These findings suggest a serial reading process, similar to how young or struggling readers approach words, which is known to be cognitively demanding (Rayner, 2009a).

The current study aimed to explore eye movements during number reading compared to words and pseudowords of matched length inserted in sentences rather than in isolation. Investigating eye movements on numbers within sentences is critical because reading behavior changes between these contexts (Clifton et al., 2007; Vitu et al., 1990). In isolated presentations, a fixation point guides attention to the correct location on the screen, influencing the initial eye movements. However, in sentence reading, eye movements follow the flow of reading, reflecting cognitive and linguistic processing (Cop et al., 2015; Rayner, 1986). Among proficient readers, fixations – periods when information is taken in – are usually observed in words of three or more letters, typically occurring in the left part of these words (in left-to-right scripts). Refixations often occur on long or rare words. Fixations last 225–275 ms, making up about 90 % of reading time. Saccades – brief, rapid eye movements between fixations – last 10–30 ms and usually cover 1 to 20 letters, with an average of 7–9 letters, representing 10 % of reading time. While saccades mostly move forward, 10–15 % are regressive, moving backward to revisit skipped or misread words (Starr & Rayner, 2001). Given the interrelated nature of sentence reading and linguistic processes, it is important to extend our previous results on isolated numerals to sentence-based contexts.

Additionally, the present study considered whether eye movements differ when numbers are read aloud or silently. Interestingly, with its verbal production of number words' stage, the aforementioned model of Dotan and Friedmann (2019) focuses on the mechanisms of reading Arabic numerals aloud. However, research suggests on the one hand that even when numbers do not need to be vocalized, influences from their corresponding verbal form occur. For example, Göbel et al. (2014) asked to German and Italian 7- to 9-year-old children to perform additions leading or not to a decade change. While additions with a decade change were executed slower by all the children (i.e., carry-effect), this effect was significantly stronger for German children, whose language reverses the tens and units digits. This suggests that the oral form corresponding to numbers is activated even in silent mathematical activities. On the other hand, in the field of word reading, several eye-tracking studies have shown that aloud reading leads to more fixations and saccades as well as longer fixations compared to silent reading (Krieber et al., 2017; Vorstius et al., 2014). This is because oralization is slower than the rate at which information is captured by the eyes. Numbers, being logographic, take longer to pronounce than words of the same length (de Chambrier et al., 2023; Rayner, 2009a). Thus, although simple exposure to numbers seems to lead to an activation of their corresponding form in silent tasks, numbers require more oral conversions compared to words of same length. We should therefore observe even fewer fixations and saccades in silent reading of numbers compared to reading aloud than between silent and aloud reading of words and pseudowords. Additionally, since reading large numerals is cognitively demanding (de Chambrier et al., 2023), and given that precise numerical details are often unnecessary for sentence comprehension, it was hypothesized that readers might skim numbers more when reading silently compared to words and pseudowords. This was additionally tested by comparing reading of rounded versus non-rounded numbers (i.e., 81'200'000 versus 18'345'672). Indeed, since non-rounded numbers require more oral conversions than rounded numbers, it was hypothesized that readers would skim non-rounded numbers more than rounded ones.

Lastly, the current study explored the proportion of leftward saccades when reading numbers compared to words and pseudowords. Since numbers increase in value from right to left but are spoken from left to right, the system requires a dual reading direction. This contrasts with words and pseudowords, which follow a consistent left-to-right grapheme to phoneme transcription. It was expected that this dual-directional requirement would result in more leftward saccades when reading numbers compared to words and pseudowords.

2. Methods

2.1. Participants

The participants included 49 psychology students from the University of Lausanne (37 women, 11 men, and 1 identified as "Other"; mean age = 20.5 years, SD = 2.62; MIN = 18, MAX = 33). All participants were proficient readers of French, had normal or corrected-to-normal vision, and reported no history of learning disorders. They received course credits in exchange for their participation. All participants gave their informed consent prior to their inclusion in the study. The study procedures adhered to the Declaration of Helsinki, and ethics approval was obtained from the University of Lausanne's ethics committee (reference: C_SSP_022021_00006) prior to the study's commencement.

2.2. Tasks and materials

Both the reading aloud and silent reading tasks involved reading sentences containing predetermined areas of interest (AOI) for eye movement analysis around rounded and non-rounded numbers, as well as matched-in-length words and pseudowords. The participants were unaware of the AOI. Each task included 16 sentences: 16 for silent reading and 16 for reading aloud, with four item types (rounded numbers, non-rounded numbers, words, and pseudowords) appearing in four different lengths (8 to 11 digits/letters). The placement of the items of interest was consistent across all items of the same length in both the silent and aloud reading conditions (see Supplementary material 1, "all items.pdf").

The numbers were displayed with thousand separators and represented real or plausible quantities, excluding overly familiar figures (e.g., world population, house prices). An example sentence with a non-rounded number was "Chaque jour, ce sont l'équivalent de 469'814'235 mètres carrés de forêt qui disparaissent en lien avec les activités humaines" ("Every day, the equivalent of 469,814,235 square meters of forest disappear as a result of human activity") in the silent condition, and "Le fleuve amazonien est le cours d'eau ayant le plus gros débit avec ses 546'813'427 mètres cubes d'eau par heure enregistrés au point le plus puissant" ("The Amazon River is the river with the highest flow rate, with 546,813,427 cubic meters of water per hour recorded at its most powerful point") in the aloud condition. A sentence with a rounded number was "C'est avec 81'200'000 voix que le démocrate Joe Biden a gagné la dernière élection américaine face au président sortant républicain Donald Trump" ("Democrat Joe Biden won the last American election against Republican incumbent Donald Trump with 81,200,000 votes") in the silent condition, and "Située à 62'700'000 km de distance, Mars est la deuxième planète la plus proche de la Terre et est atteignable en un peu plus d'un mois avec un vaisseau rapide" ("Located 62,700,000 km away, Mars is the second closest planet to Earth and can be reached in just over a month with a fast spacecraft") in the aloud condition.

Non-rounded numbers in the aloud and silent conditions were matched by the number of syllables in their spoken forms and by their order of magnitude. They contained no more than two identical digits, and any repeated digits were separated by at least four positions. For instance, the number 12'819'245'763 was paired with 13'723'468'249 (both 20 syllables in French). Rounded numbers, which featured more trailing zeros than precise digits, were similarly matched by syllable count and magnitude. For example, 213'700'000 was paired with 215'800'000 (both 8 syllables in French).

The words of interest in both the silent and aloud reading conditions were rare, with frequencies ranging from 0 to 1.29 according to Lexique.org. They were matched in length to the numbers, counting thousand separators as symbols. For example, the number 469'814'235 (9 digits and 2 thousand separators) was paired with an 11-letter word. Words of the same length in both conditions were matched by grammatical category and syllable count. For instance, for a 10-letter length, the word in the reading aloud task was "abnégation" (abnegation), a feminine noun with four syllables, and in the silent reading task, it was "déconvenue" (disappointment), also a feminine noun with four syllables. The sentences were constructed so that the target words were unpredictable, such as in "Avec abnégation, un homme âgé a offert l'une de ses rares bouteilles d'oxygène de réserve à un enfant qui rencontrait des difficultés respiratoires ("With self-sacrifice, an elderly man offered one of his rare spare oxygen bottles to a child who was having difficulty breathing") in the silent condition and "Quelle déconvenue pour cette mère de famille investie d'apprendre que son fils avait quitté le lycée et qu'il voulait en faire autant pour le domicile familial" ("What a disappointment it was for this committed mother to learn that her son had left high school and wanted to do the same for the family home") in the aloud condition.

Pseudowords were matched to the words in terms of letter count and phonological complexity. Letters corresponding to occlusive phonemes (t, d, p, etc.) were swapped, as were those for vocalic phonemes (a, u, i, é, etc.) and long consonant phonemes (fricative, nasal, or lateral: s, n, l). For example, the pseudoword "égrapufion" was matched to the word "abnégation" in the sentence "Après égrapufion, ces députés ont décidé d'obliger les multinationales à payer un impôt minimal quel que soit le pays où elles installent leur siège" ("After égrapufion, the members of Parliament decided to force multinationals to pay a minimum tax regardless of the country in which they are based").

Therefore, AOI length (characters, including spaces) was perfectly matched across Condition (Silent vs Aloud) for each item and showed identical distributions across Stimulus Type (words, pseudowords, rounded, non-rounded): mean $\pm$ SD = 12.0 $\pm$ 1.83 in all cells. A two-way ANOVA (Stimulus Type $\times$ Condition) detected no main effects or interaction (all F $\approx$ 0, p = 1.00), confirmed by nonparametric tests (Wilcoxon paired test p = 1.00; Kruskal–Wallis p = 1.00). Thus, AOI length was fully balanced across materials. Table 1 displays the 32 stimuli corresponding to the AOIs that served as the basis for the eye-movement analyses.

To ensure participants processed the sentences semantically, each sentence was followed by a literal comprehension question (32 in total), and participants had to select one of three answers. For example, after the sentence about the disappointed mother, the question was: "What has this son left behind? a) His native country; b) His girlfriend; c) High school." The correct answer's position varied across questions.

Additionally, to gauge how attentively participants read the numbers silently, without overtly drawing attention to the numerical information, two questions focused on the order of magnitude of non-rounded numbers in the silent condition. For instance, after the sentence about 469,814,235 square meters of forest disappearing daily, participants answered the question: "Approximately how many square meters of forest disappear every day? a) 400 million; b) 40 million; c) 400 billion."

Each trial consisted of the sequential presentation of a target sentence, followed by an initial blank screen, a question item, and a second blank screen, all shown against a gray background (Fig. 1). The trial began with a drift check, where the experimenter ensured the participant's gaze was centered on a black circle with a diameter of 0.48°. The target sentence remained visible until the participant pressed the space bar. Afterward, a blank screen appeared for 100 ms, followed by a multiple-choice question that the participant answered by selecting one of three options using the keyboard. Following the response, a blank screen was shown for 1000 ms before the next trial began. Participants completed two blocks of trials: the silent reading block and the reading aloud block. To ensure natural reading mechanisms in the silent reading condition, participants always started with the silent reading block to avoid any influence from prior aloud reading task.

Before starting the silent reading block, participants completed three

Table 1
AOI stimuli used for the eye-movement analyses.

	Silent	Aloud
Non-rounded	18'345'672	19'571'534
Rounded	81'200'000	62'700'000
Words	abnégation	déconvenue
Pseudowords	égrapufion	gadoufinée
Non-rounded	469'814'235	546'813'427
Rounded	213'700'000	215'800'000
Words	recensement	désignation
Pseudowords	firoulemond	parichélieu
Nonrounded	3'267'154'298	3'456'178'952
Rounded	2'360'000'000	4'530'000'000
Words	simultanément	excessivement
Pseudowords	fénortilement	astouliréments
Non-rounded	12'819'245'763	13'724'368'259
Rounded	24'860'000'000	23'670'000'000
Words	hypoglycémique	polysyllabique
Pseudowords	appiclorédoule	pattirolémique

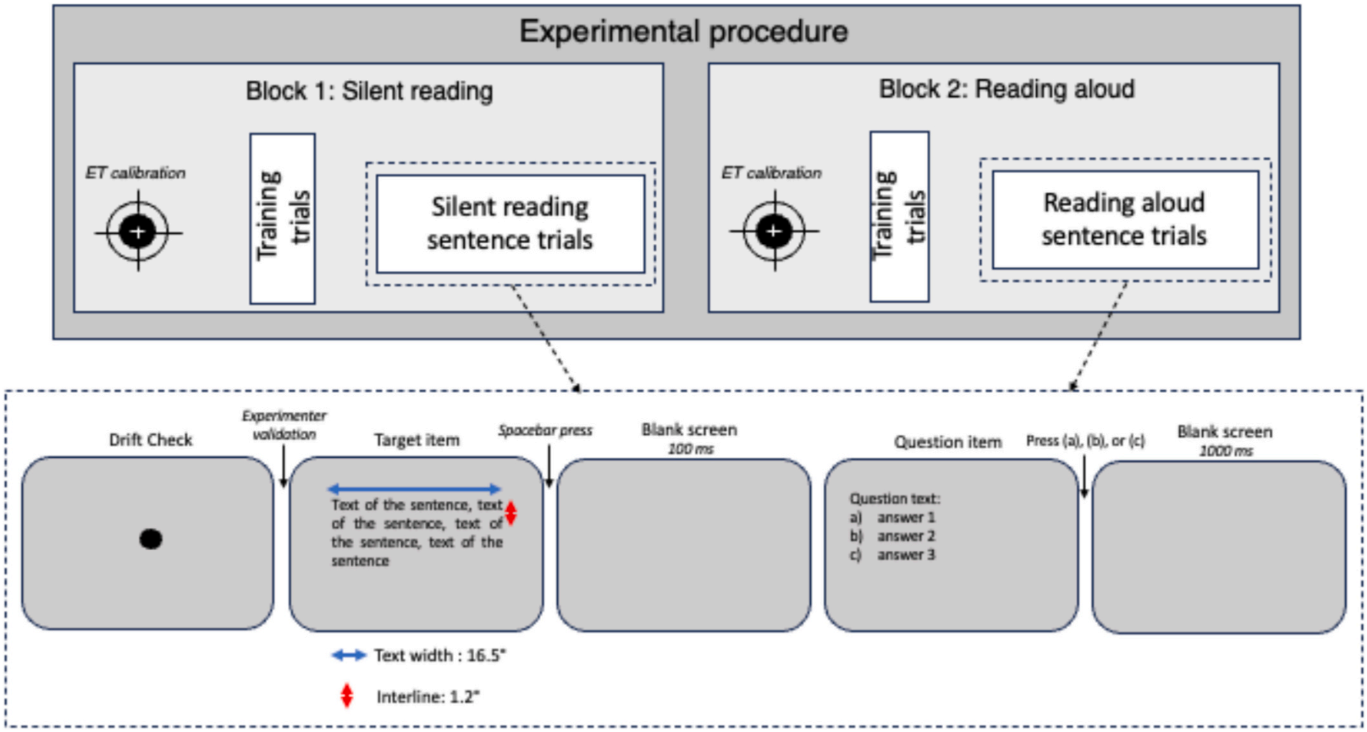

Fig. 1. Experimental procedure and trial dynamics.

training trials: one sentence with a target word, one with a target rounded number, and one with a target pseudoword, each followed by a comprehension question. Participants were instructed to press the spacebar to advance to the next screen and practiced responding to multiple-choice questions. They were informed that some words were meaningless and should be read as if they were regular French words. The experiment used a fully within-subjects design, with all participants completing all conditions (silent vs. aloud; words, pseudowords, rounded numbers, and non-rounded numbers). Sentence order was randomized in both the silent and aloud blocks. In the silent block, two additional constraints were applied: the block never started with a magnitude-related question, and no two such questions occurred consecutively. These constraints reduced undue focus on numerical magnitude and ensured an even distribution of all stimulus types (words, pseudowords, rounded numbers, non-rounded numbers), thereby minimizing material and sequence effects.

The reading aloud block began with four training trials: one sentence with a target word, one with a target pseudoword, one with a rounded number, and one with a non-rounded number. Participants were again informed that some words were meaningless and should be read as if they were French words. Corrective feedback was provided during these training trials to reduce mistakes in the experimental phase.

2.3. Procedure

Participants were seated individually in a dimly lit, quiet room, positioned 930 mm from a 24-inch LCD monitor (screen dimensions: 520 × 325 mm) with a resolution of 1920 × 1200 and a 60 Hz refresh rate. To ensure consistent head positioning throughout the experiment, both a chin and forehead rest were used.

The "hole-in-card" test was employed to determine ocular dominance, where participants centered their gaze through a small hole. The dominant eye's gaze position was tracked using an EyeLink 1000 eye tracker (SR Research Ltd., ON, Canada) with a 35-mm aperture lens setup. The eye tracker, positioned 530 mm in front of the participants, recorded gaze data at a sampling rate of 1000 Hz. The readable text area width for sentence presentation was 16.5° of visual angle, with an interline spacing of 1.2° (see Supplementary material 2, "stimuli examples.pdf"). To ensure optimal eye tracking, the eye tracker camera was focused on the participant's eyes by adjusting the lens-focusing ring until a clear image of the pupil was obtained. The pupil was centered when participants fixated on the middle of the screen. Pupil and corneal reflection thresholds were set automatically using EyeLink's auto-thresholding feature, with criteria defined by a pupil threshold between 75 and 110 and a corneal reflection threshold below 230. Adjustments to the illumination output were made based on pupil threshold levels as necessary.

A 9-point automatic calibration and validation procedure was carried out before each block (silent and aloud reading). The calibration process was repeated until the maximum validation offset was less than 1° and the average validation offset was below 0.5°.

2.4. Software

The experiment was designed and implemented using Experiment Builder software (https://www.sr-research.com). Data processing and exportation were carried out with the Data Viewer analysis software, while all statistical analyses were conducted using MATLAB 9.12 (The MathWorks Inc., Natick, MA).

2.5. Outcomes

2.5.1. Accuracy

We recorded error rate made while reading the items for the items of interest in the reading aloud condition, coding each participant's response as 0 for incorrect and 1 for correct. Additionally, accuracy for the comprehension questions was registered for both the silent and aloud reading conditions.

2.5.2. Eye-tracking variables

Eye-movement data were first parsed online using the EyeLink 1000 internal saccade/fixation detector (SR Research Ltd., 2018) configured in Cognitive mode, which applies velocity and acceleration thresholds of 30°/s and 8000°/s^2, respectively, and 0.1° motion threshold for saccade detection. These parameters are optimized for cognitive and psycholinguistic tasks and correspond to those recommended in the EyeLink 1000 User Manual (v.1.52). Velocity estimates were computed using a five-point moving average of raw gaze samples (1 kHz). Blinks were detected based on the loss of pupil signal and confirmed using a 12 ms offset window. Samples within blinks and invalid data were excluded. No additional spatial filtering or baseline correction was applied, and drift correction was performed before each trial. The starting and ending positions of the saccades (horizontal and vertical screen coordinates in pixels) were used to determine their direction, whether towards the left or right. Blinks, detected as "saccades containing a blink" by the EyeLink system (SR Research Ltd., 2018), were excluded from all analyses. Saccades were counted as belonging to an AOI only when both their starting and ending positions fell within the AOI; saccades that merely originated from or terminated in the AOI were not included.

Before each stimulus, a drift check was conducted by having participants fixate on a black circle at the center of the screen (Fig. 1). Once the experimenter verified the participant's fixation, they pressed a button to display the sentence, ensuring that the participant was already focused on the center of the screen at the beginning of the trial.

2.6. Data analysis

The experimental conditions corresponded to four classes of items that were randomly presented to participants for reading: words, pseudowords, rounded numbers, and non-rounded numbers. Forty-nine participants read a total of 32 items each, resulting in 1568 trials. The data collected in the study are provided in the OSF repository (https://osf.io/s7gmn/). The data were visualized using violin plots to describe the distribution of results across the experimental conditions. Due to the nonnormal distribution of the data, medians and interquartile ranges (IQRs) were used to represent central tendencies and dispersion. Additional histograms displaying frequency distributions were included in the Supplementary material 3 ("Regression Models.pdf").

For inferential statistics, generalized linear mixed regression models were applied to account for the hierarchical structure of the data (saccades/fixations nested within items, and items nested within participants) and the nonnormal distributions. Five models were constructed, one for each key variable: fixation number, saccade number, fixation duration, saccade amplitude, and leftward saccades (adjusted for the number of rightward saccades to control for the total number of saccades). The gamma distribution with a log link was used for modeling these outcomes. An assessment of the gamma distribution against the sample data is detailed in the Supplementary material 3.

Key details for the regression models are:

- The models accounted for stimulus type (words, pseudowords, rounded numbers, non-rounded numbers) and reading condition (silent or aloud). Both were treated as categorical variables and converted into dummy variables.
- In the fifth model, the number of rightward saccades was included as a continuous covariate to adjust for overall saccade numbers.

The random effects structure varied by model:

- For the fixation and saccade number models, a random slope term was included to account for the participant's varying response to different stimulus types (participant-stimulus type interaction).
- For fixation duration and saccade amplitude models, a two-level hierarchy was implemented with saccades/fixations nested in trials, nested in participants. To achieve computational convergence, the random effects were limited to an intercept term.

The significance level was set at $\alpha = 0.01$. The full model outputs, including details of fixed and random effects, are available in the Supplementary material 3. Additionally, the estimated fixed effects were overlaid on the violin plots to illustrate the marginal effects. In interpreting the fifth model (leftward saccades), it is important to consider that the continuous covariate (number of rightward saccades) was not reflected in the displayed estimated effects.

From a cognitive standpoint, fixations represent periods of visual information uptake and are closely linked to attentional allocation and processing demands (Rayner, 2009b). Longer fixation durations and higher fixation counts typically indicate increased processing effort, as seen with rare words, complex numbers, or unpredictable content. Saccades correspond to rapid shifts of overt attention between fixation targets; shorter or more frequent saccades generally reflect greater visual exploration or localized processing difficulty. Leftward (regressive) saccades denote re-inspection of previously read material, often associated with ambiguity resolution, syntactic reanalysis, or integration challenges. Collectively, these indicators provide sensitive and well-established measures of cognitive load and information processing during sentence reading and numerical decoding.

3. Results

3.1. Error rate of read aloud items

For the items read aloud, participants made 48 mistakes out of 784 trials, corresponding to an average error rate of 6.1 %. The majority of errors occurred with non-rounded numbers ($n = 22$), followed by rounded numbers ($n = 21$), and pseudowords ($n = 5$). Notably, no mistakes were recorded for words. Given the low frequency of errors, all items were retained for the analyses (Table 2).

3.2. Error rate of comprehension questions

The percentage of incorrect responses to the comprehension questions following the sentences was 1.9 % in the reading aloud condition, where no questions about order of magnitude were asked. In the silent reading condition, questions unrelated to the order of magnitude resulted in a 2.3 % error rate, while the two questions specifically addressing the order of magnitude led to a significantly higher error rate of 26 % (Table 3).

3.3. Fixation number

The generalized linear mixed model revealed a significant fixed effect of stimulus type (all $p < 0.001$), indicating that the number of fixations increased from words to non-rounded numbers, passing through pseudowords and rounded numbers. Participants made up to twice as many fixations when reading rounded numbers compared to words and up to 2.75 times more fixations when reading non-rounded numbers compared to words (Fig. 2). There was no significant main effect of condition ($p = 0.18$), suggesting that reading aloud and reading silently did not result in significantly different amounts of fixations. Finally, we found a significant interaction between stimulus type and condition for non-rounded numbers only ($p < 0.001$). Non-rounded numbers elicited fewer fixations when read silently (median = 7) compared to aloud (median = 11) (Table 4).

Table 2
Error rate on each type of items in the read aloud condition.

Read aloud items	Nb of trials	Nb of error	% of error
Words	196	0	0 %
Pseudowords	196	5	2,7 %
Rounded numbers	196	21	11,4 %
Non-rounded numbers	196	22	12 %
Total	**784**	**48**	**6,1 %**

Table 3
Error rate on the different comprehension questions according to reading condition.

Reading condition	Type of comprehension question	Nb of trials	Nb of error	% of error
Silent reading	Unrelated to the order of magnitude	686	15	2,2 %
	Related to the order of magnitude	98	24	24,5 %
Aloud reading	Unrelated to the order of magnitude	784	15	1,9 %
	Total	**1568**	**54**	**3,4 %**

3.4. Saccade number

The generalized linear mixed model revealed a significant fixed effect of stimulus type (all $p < 0.001$), indicating that the number of saccades increased progressively from words to non-rounded numbers, passing through pseudowords and rounded numbers. Participants made 2.5 times more saccades when reading rounded numbers compared to words, and up to 4 times more saccades when reading non-rounded numbers compared to words (Fig. 3). There was no significant effect of condition ($p = 0.27$), indicating that reading aloud and reading silently did not result in significantly different numbers of saccades. Lastly, we found a significant interaction between stimulus type and condition only for non-rounded numbers ($p < 0.001$), which resulted in a lower number of saccades when read silently (median = 5) compared to reading aloud (median = 8) (Table 5).

3.5. Fixation duration

The generalized linear mixed model revealed a significant fixed effect of stimulus type (all $p < 0.001$), indicating that fixation duration generally increased from words to non-rounded numbers, passing through pseudowords and rounded numbers. Fixation duration increased by up to 43 ms for rounded numbers compared to words, and by up to 78 ms for non-rounded numbers compared to words (Fig. 4). There was also a significant effect of condition ($p < 0.005$), showing that reading aloud resulted in 9 % longer fixations (global median = 266 ms) compared to silent reading (global median = 241 ms). Finally, a significant interaction was found between stimulus type and condition only for non-rounded numbers ($p < 0.001$), which had 49 ms shorter fixation durations when read silently (median = 249 ms) compared to reading aloud (median = 298 ms) (Table 6).

3.6. Saccade amplitude

The generalized linear mixed model revealed a significant fixed effect of stimulus type (all $p < 0.001$), indicating a global decrease in saccade amplitude from words to non-rounded numbers (passing through pseudowords and rounded numbers). Saccade amplitude decreased by up to 0.19° when reading rounded numbers compared to words, and by up to 0.34° when reading non-rounded numbers compared to words (Fig. 5). There was no significant effect of condition ($p = 0.11$), suggesting that reading aloud did not result in different saccade amplitudes compared to silent reading. Additionally, we identified a significant interaction between stimulus type and condition only for non-rounded numbers ($p < 0.001$), where saccades were 0.17° larger when read silently (median = 0.79°) compared to aloud (median =

Table 4
Fixation number: Fixed Effects (GLMM).

Term	Estimate	SE	t-Stat	DF	p-Value
(Intercept, Words, Loud)	1.451	0.050	29.229	1559	<0.001
Stimulus: Pseudowords	0.412	0.048	8.536	1559	<0.001
Stimulus: Numerals (rounded)	0.735	0.054	13.592	1559	<0.001
Stimulus: Numerals (non-rounded)	0.978	0.056	17.460	1559	<0.001
Practice status: silence	−0.063	0.047	−1.351	1559	0.177
Stimulus: Pseudowords × Practice status: silence	−0.057	0.066	−0.869	1559	0.385
Stimulus: Numerals (rounded) × Practice status: silence	−0.155	0.066	−2.342	1559	0.019
Stimulus: Numerals (non-rounded) × Practice status: silence	−0.369	0.066	−5.580	1559	<0.001

Note. Estimates are on the log scale (Gamma link = log). SE = standard error; DF = Satterthwaite degrees of freedom.

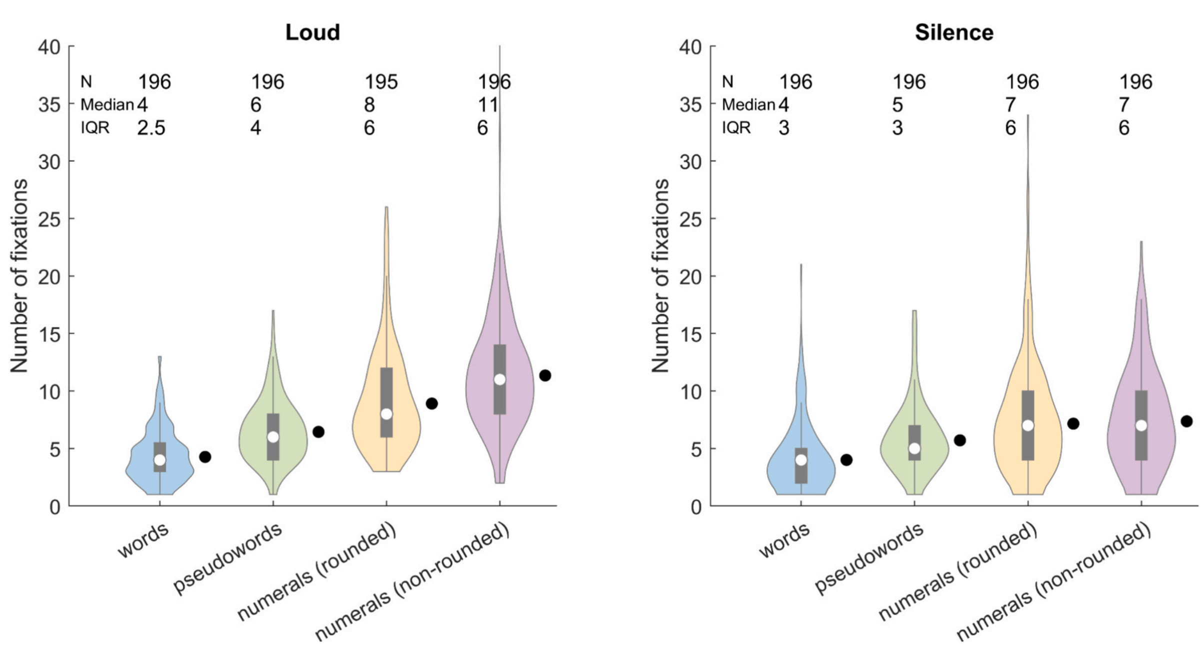

Fig. 2. Fixation number. Violin plots illustrate the distribution of raw data. Black dots represent values predicted by the generalized linear model. $N = 1567$ (32 trials per 49 participants, with one trial lacking recorded fixations). IQR = interquartile range.

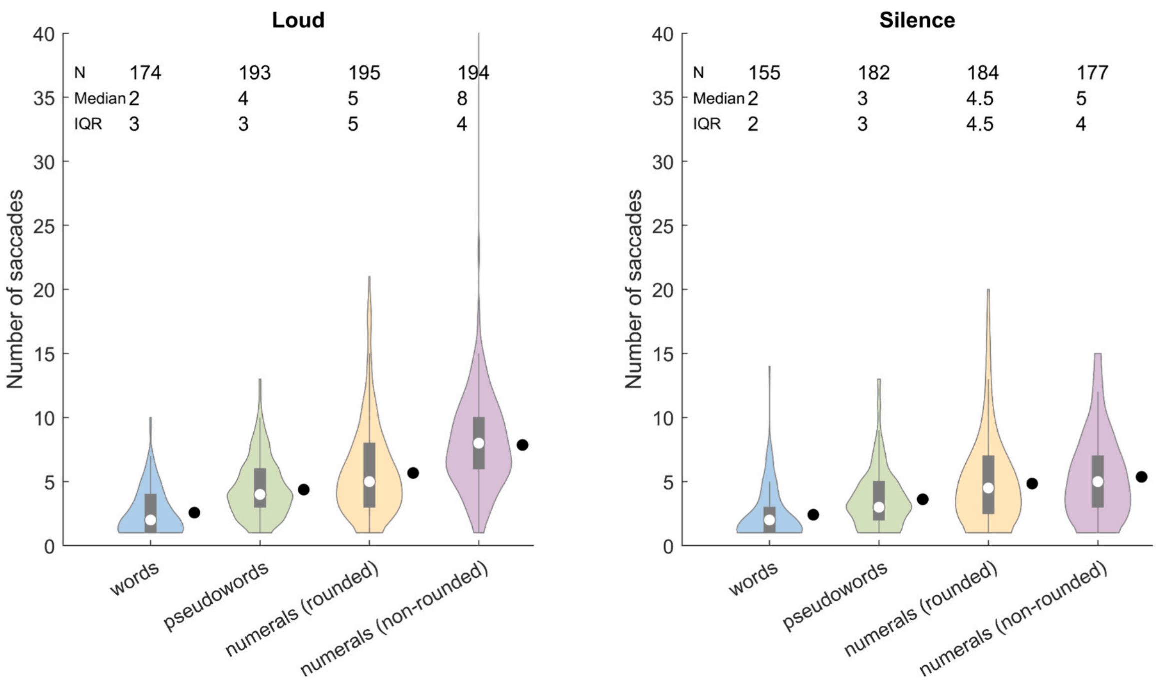

Fig. 3. Saccade number. Violin plots illustrate the distribution of raw data. Black dots denote values predicted by the generalized linear model. $N = 1454$ trials (32 trials × 49 participants, with some trials missing recorded saccades). IQR = interquartile range.

Table 5
Saccade number: Fixed Effects (GLMM).

Term	Estimate	SE	t-Stat	DF	p-Value
(Intercept, Words, Loud)	0.946	0.059	16.095	1446	<0.001
Stimulus: Pseudowords	0.530	0.057	9.369	1446	<0.001
Stimulus: Numerals (rounded)	0.790	0.062	12.789	1446	<0.001
Stimulus: Numerals (non-rounded)	1.116	0.066	16.939	1446	<0.001
Practice status: silence	−0.065	0.059	−1.105	1446	0.269
Stimulus: Pseudowords × Practice status: silence	−0.125	0.080	−1.548	1446	0.122
Stimulus: Numerals (rounded) × Practice status: silence	−0.092	0.080	−1.148	1446	0.251
Stimulus: Numerals (non-rounded) × Practice status: silence	−0.316	0.081	−3.915	1446	<0.001

Note. Estimates are on the log scale (Gamma link = log). SE = standard error; DF = Satterthwaite degrees of freedom.

0.62°) (Table 7).

3.7. Saccade direction: number of leftward saccades

The generalized linear mixed model revealed a significant fixed effect of stimulus type (all $p < 0.001$), indicating a global increase in the number of leftward saccades from words to non-rounded numbers (including pseudowords and rounded numbers). Specifically, the number of leftward saccades increased by 43 % when reading pseudowords compared to words, by 85 % when reading rounded numbers compared to words, and by 70 % when reading non-rounded numbers compared to words (Fig. 6). When grouping words and pseudowords versus rounded numbers and non-rounded numbers, there was a 42 % increase in the number of leftward saccades when reading numbers compared to words. There was no significant effect of condition ($p > 0.01$), indicating that reading aloud did not result in a different number of leftward saccades compared to silent reading. There were no significant interactions between stimulus type and condition (Table 8).

4. Discussion

Building on previous research, this study aimed to investigate eye movements when reading numbers in sentences, considering two reading conditions (aloud or silent) and whether the numbers were rounded or non-rounded. We hypothesized that large numbers would be skimmed more during silent reading, leading to differences in fixation and saccade patterns compared to pseudowords. Additionally, we explored whether non-rounded numbers, requiring more cognitive effort, would show greater discrepancies between oral and silent reading. Lastly, we compared leftward saccades during number reading with those seen in word and pseudoword reading, given the right-to-left scanning required for interpreting numerical magnitude.

4.1. Fixation number and duration, saccade number and amplitude

The eye movement pattern observed in our previous study (de Chambrier et al., 2023) were extended in this research. Numbers prompted more frequent and longer fixations, as well as more frequent but shorter saccades compared to matched words and pseudowords. In our previous study, these results were obtained with isolated, non-rounded items that were read aloud. Here, they were found in rounded and non-rounded numbers, inserted in sentences, and read aloud or silently. Overall, it is interesting to find these same findings under reading conditions that have been shown to influence eye movements when reading words. These conditions include fewer fixations and saccades, as well as shorter fixations in silent reading compared to reading aloud (Krieber et al., 2017; Vorstius et al., 2014) and in text reading compared to reading isolated words (Clifton et al., 2007; Vitu et al., 2004). This pattern of eye movements – more frequent and longer fixations as well as more frequent and shorter saccades – is similar to that observed in young and struggling readers when making print-to-sound correspondences, and reflects the high cognitive load associated with step-by-step reading (Rayner, 2009a). Therefore, the current study confirms the extent to which reading large numerals requires a serial conversion process compared to matched phonographic items, across the different modalities studied here.

However, differences in eye movements still emerged based on

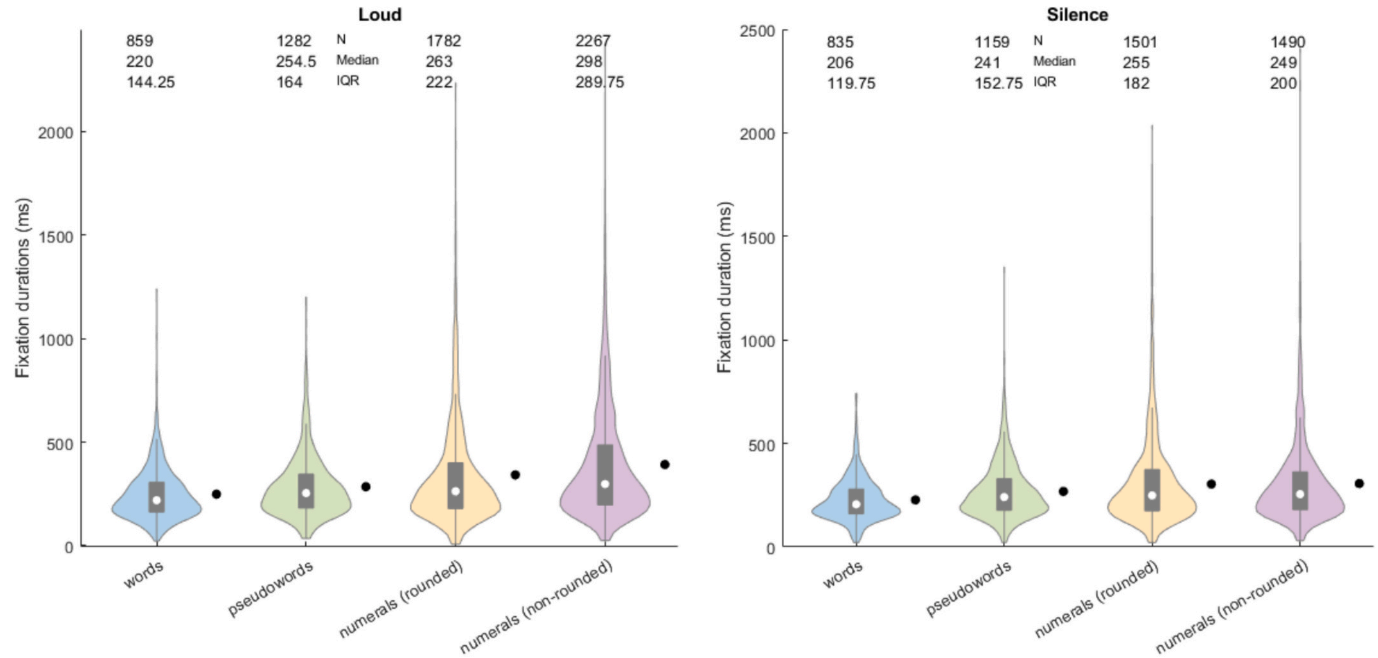

Fig. 4. Fixation duration. Violin plots show the distribution of raw data, with black dots representing the values predicted by the generalized linear model. N = 11,175 (32 trials × 49 participants × all recorded fixations). IQR = interquartile range.

Table 6
Fixation duration: Fixed Effects (GLMM).

Term	Estimate	SE	t-Stat	DF	p-Value
(Intercept, Words, Loud)	5.517	0.031	178.790	11,167	<0.001
Stimulus: Pseudowords	0.136	0.027	5.016	11,167	<0.001
Stimulus: Numerals (rounded)	0.318	0.026	12.441	11,167	<0.001
Stimulus: Numerals (non-rounded)	0.455	0.025	18.471	11,167	<0.001
Practice status: silence	−0.091	0.031	−2.933	11,167	0.003
Stimulus: Pseudowords × Practice status: silence	0.029	0.039	0.753	11,167	0.451
Stimulus: Numerals (rounded) × Practice status: silence	−0.028	0.037	−0.761	11,167	0.447
Stimulus: Numerals (non-rounded) × Practice status: silence	−0.157	0.036	−4.315	11,167	<0.001

Note. Estimates are on the log scale (Gamma link = log). SE = standard error; DF = Satterthwaite degrees of freedom.

whether the items were read silently or aloud, and whether the numbers were rounded or not. Specifically, reading condition (silent vs. aloud) significantly influenced fixation duration, which was 9 % longer during aloud reading. This aligns with the aforementioned previous findings in word reading, where eye movements tend to slow down because the eyes typically move faster than speech production, causing fixations to last longer to avoid getting ahead of the voice (Rayner, 2009a; Vorstius et al., 2014). Importantly, this condition effect interacted with stimulus type. For non-rounded numbers, silent reading resulted in significantly fewer and shorter fixations, as well as fewer and larger saccades. This supports our hypothesis that when readers are not required to vocalize numbers, they tend to skim over them, likely due to the high cognitive demand of converting each digit into its spoken form. This is further suggested by the high error rate (26 %) when participants answered questions about the order of magnitude of the numbers they had just read. The fact that this pattern was only observed for non-rounded numbers suggests that the cognitive load is reduced for rounded numbers, which contain fewer digits to be converted into oral forms.

4.2. *Leftward saccades*

As hypothesized, the proportion of leftward saccades was higher for numbers than for words and pseudowords. This can be attributed to the right-to-left orientation inherent in number reading, whereby an increase in the size of numbers is reflected by digits added on the left, with each rank being worth 10 times more than the previous one (Ifrah, 2000). This higher proportion of leftward saccades had not been observed in our previous study. In that study, the fixation point was presented before the isolated items and was located at the middle point of the items. This resulted in initial leftward saccades for many items, including words and pseudowords. In the current study, numbers inserted in sentences resulted in 42 % more leftward saccades than words and pseudowords, while the typical leftward saccades proportion in text reading is 10–15 % (Starr & Rayner, 2001). Interestingly, this higher proportion of leftward saccades was observed even for rounded numbers – the easiest numbers to read – compared to pseudowords, the most challenging phonographic items. The higher percentage of leftward saccades typically observed with pseudowords compared to words is due to the fact that this type of item is processed by the sublexical phonological rather than the lexical procedure (Coltheart et al., 2001; De Luca et al., 2002). For numbers, the even higher percentage of leftward saccades is likely related to the need to scan these numbers from the right to determine the order of magnitude of the first digits on the left of the number (or in other words, to determine that in 81,200,000, 81 corresponds to 81 million). This is supported by the finding that even rounded numbers, which do not require an oral conversion of each digit, result in more leftward saccades than pseudowords, which require processing of entire sublexical units. Thus, the right-to-left reading orientation of numbers is clear here, with numerals put in a context of natural reading flow. As far as we know, this is the first time the impact of this positional system on how the numbers have to be read has been empirically traced.

4.3. *Limitations and further prospects*

Several limitations of the current study must be taken into account. Firstly, the study design may not fully reflect real-world reading

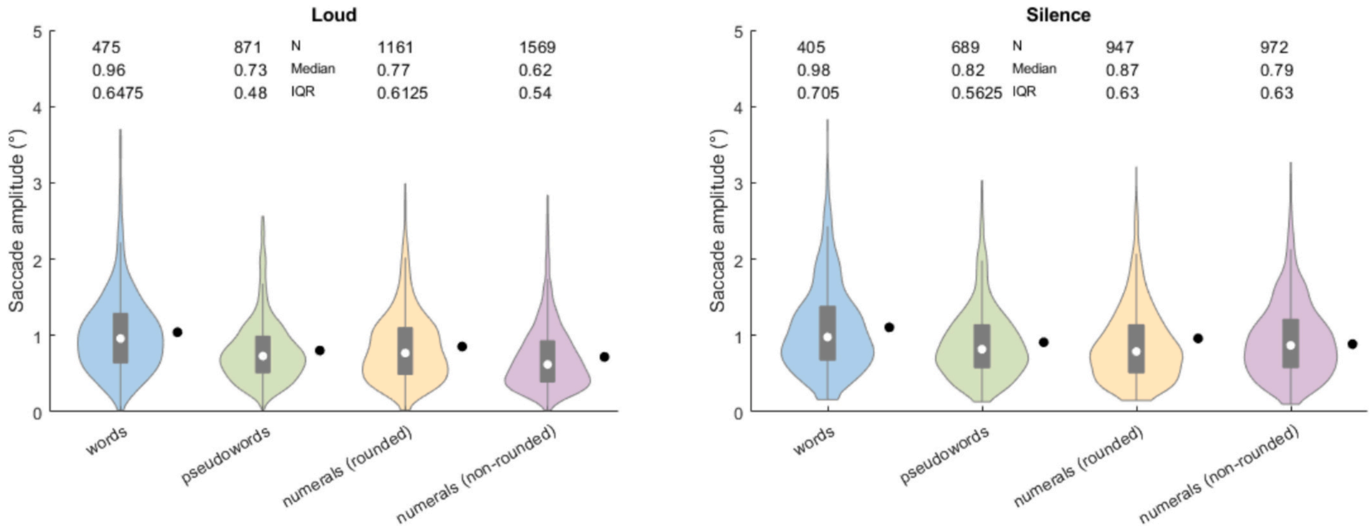

Fig. 5. Saccade amplitude. Violin plots display the distribution of raw data. The black dots represent values predicted by the generalized linear model. $N = 7089$ (32 trials × 49 participants × all recorded saccades). IQR = interquartile range.

Table 7
Saccade amplitude: Fixed Effects (GLMM).

Term	Estimate	SE	t-Stat	DF	p-Value
(Intercept, Words, Loud)	0.041	0.031	1.324	7081	0.185
Stimulus: Pseudowords	−0.260	0.031	−8.371	7081	<0.001
Stimulus: Numerals (rounded)	−0.197	0.030	−6.627	7081	<0.001
Stimulus: Numerals (non-rounded)	−0.370	0.029	−12.922	7081	<0.001
Practice status: silence	0.060	0.037	1.608	7081	0.108
Stimulus: Pseudowords × Practice status: silence	0.066	0.046	1.426	7081	0.154
Stimulus: Numerals (rounded) × Practice status: silence	0.057	0.044	1.300	7081	0.194
Stimulus: Numerals (non-rounded) × Practice status: silence	0.149	0.043	3.453	7081	<0.001

Note. Estimates are on the log scale (Gamma link = log). SE = standard error; DF = Satterthwaite degrees of freedom.

environments. Differences in reading mechanisms have been observed depending on whether the text is on paper or digital, and further research could investigate whether such influences also occur when reading numbers. Additionally, the observed results could be affected by individual differences such as numeracy skills, prior experience with numbers, and reading proficiency. Although numeracy was not assessed in our sample, individuals with higher numeracy may process non-rounded numbers more quickly, requiring fewer fixations and saccades. Furthermore, a greater number of stimuli (here, 32 stimuli in

Table 8
Saccade direction, regressions (left saccades): Fixed Effects (GLMM).

Term	Estimate	SE	t-Stat	DF	p-Value
(Intercept, Words, Loud)	−0.440	0.082	−5.355	1445	<0.001
Stimulus: Pseudowords	0.359	0.080	4.479	1445	<0.001
Stimulus: Numerals (rounded)	0.618	0.086	7.175	1445	<0.001
Stimulus: Numerals (non-rounded)	0.563	0.092	6.125	1445	<0.001
Right saccade number	0.175	0.079	2.204	1445	0.028
Practice status: Silence	0.152	0.011	14.322	1445	<0.001
Stimulus: Pseudowords × Practice status: silence	−0.213	0.109	−1.960	1445	0.050
Stimulus: Numerals (rounded) × Practice status: silence	−0.117	0.109	−1.081	1445	0.280

Note. Estimates are on the log scale (Gamma link = log). SE = standard error; DF = Satterthwaite degrees of freedom.

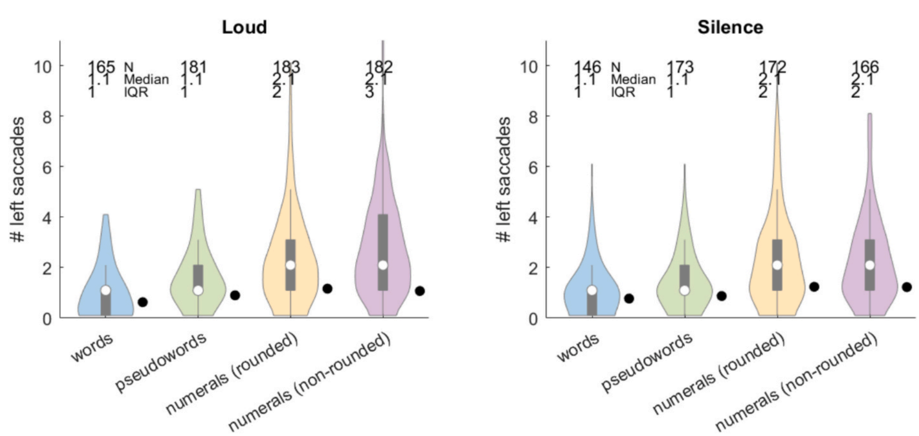

Fig. 6. Number of leftward saccades. Violin plots depict the distribution of raw data. Black dots indicate values predicted by the generalized linear model. $N = 1368$ (32 trials × 49 participants, with some trials lacking saccades). IQR = interquartile range.

total, i.e. 4 sentences under each condition) would have ensured a stronger validity of the results. Regarding the comparison between the silent and the aloud conditions, the silent condition was always administered first to capture spontaneous reading, and magnitude questions were only included in this condition to avoid drawing attention to numerical size. While this choice was deliberate, it reduces comparability with the aloud condition: order effects cannot be ruled out, and it remains unclear whether the correct response rate for magnitude would have been higher in the aloud condition. Additionally, unlike in the aloud condition, no practice items with non-rounded numbers were provided before the silent condition, which may also have impacted comparability. Furthermore, the present results concern the reading of numbers in French, the syntax of which is very similar to that of English. Other studies could investigate eye movements when reading numbers read in different languages. Referring to the word frame representing the structure of numbers in Dotan and Friedmann's (2018) model, it would be interesting to test whether different eye movements occur when reading sequences of tens and units that are reversed such as in German (i.e. vocalized from right to left). Finally, eye-tracking models such as E-Z Reader or SWIFT focus on whether lexical recognition mechanisms are serial or parallel when reading texts. In our study, although the numerals were inserted into sentences, we focused on specific areas of interest (AOIs), namely on particular items (numbers, words, and pseudowords). By studying continuous eye movements over sentences or texts, future studies could determine whether the reading processes are rather serial, such as assumed in the E-Z reader model, or parallel, such as assumed in the SWIFT model. While the current study suggests that long numbers are processed serially, this may not be the case for shorter numbers, which are processed more in parallel within them (Bahnmueller et al., 2016) and may be processed in parallel with words surrounding them, at least partially.

5. Conclusion

This study confirms that reading large numbers imposes a significant cognitive burden, even for rounded numbers, which are generally easier to process. Readers tend to reduce this burden when possible, particularly when non-rounded numbers are read silently (see the video provided as Supplementary material 4, on which eye movements between the silent and aloud condition are presented). These findings have practical implications for various fields such as education, finance, and data presentation. In educational contexts, simplifying numerical data or providing additional support when teaching large or complex numbers could enhance comprehension. Being aware of the mixture of the two writing systems coexisting when sentences contain numbers can also lead to educational opportunities, such as brief training exercises for students in this type of situation, or at least an explanation of such scenario. Such measures could be particularly useful for students who face difficulty reading in either writing system. In finance and business, simplifying numerical information in reports and presentations may improve decision-making, particularly for non-experts. Additionally, software and user interfaces could be designed to present numerical information in more accessible ways, such as with visual aids or by breaking down large numbers into smaller, more manageable units.

On the other hand, when precise number comprehension is required, such as when children are learning to read large numbers, asking them to read the numbers aloud may help reinforce their understanding and improve numeracy. More broadly, incorporating specific training in reading large numbers in school curriculums could benefit children by enhancing their ability to process challenging numerical information. Future research could explore this further by replicating this experiment with children, potentially using smaller numbers, and by developing training programs to assess whether targeted practice can reduce the cognitive load associated with reading large numbers.

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CRediT authorship contribution statement

Anne-Françoise de Chambrier: Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Philippe Terrier:** Formal analysis, Data curation. **Paolo Ruggeri:** Writing – review & editing, Visualization, Software, Project administration, Methodology. **David Müller:** Software, Methodology, Data curation. **Myrto Atzemian:** Writing – review & editing, Methodology. **Catherine Thevenot:** Writing – review & editing, Project administration, Methodology. **Marco Pedrotti:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

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Declaration of competing interest

Authors have no financial relationship with the organization that sponsored the research and have full control of all primary data.

Data availability

The data are available on the OSF repository here https://osf.io/s7gmn/ and this is indicated in the text.

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