Individual Differences in Leveraging Regularity in Emergent L2 Readers in Rural Côte d'Ivoire

Brice, Henry[1], Zinzser, Benjamin[2], Kablan, Danielle[3], Tanoh, Fabrice[4], Nana, Konan N. N.[3], Jasińska, Kaja K.[1,5]

[1] *University of Toronto, Canada* [2] *Swarthmore College, PA, USA*
[3] *Université Félix Houphouët-Boigny, Côte d'Ivoire*
[4] *Université Péléfero Gon Coulibaly, Côte d'Ivoire*
[5] *Haskins Laboratories, CT, USA*

Purpose: Statistical learning (SL) approaches to reading maintain that proficient reading requires assimilation of the rich statistical regularities in the writing system. Reading skills in developing first- and second-language readers in English have been shown to be predicted by individual differences in sensitivity to regularities in mappings from orthography to phonology (O-P) and semantics (O-S), with good readers relying more on O-P consistency, and less on O-S associations. However, SL and its relation to reading has been primarily studied in English readers in high-income Western countries.
Method: We examine individual differences in sensitivity to regularities in emergent French readers in rural agricultural communities in Côte d'Ivoire (N=134). **Results:** We show that, in contrast to previous studies, in this cohort better readers are leveraging semantic associations more strongly, while individual differences in sensitivity to orthographic consistency did not predict reading skill. Relatively little variance in reading skill was explained by sensitivity to regularities. This showcases the importance of cross-linguistic and cross-cultural research to back up universal theories of literacy, and suggests that current SL accounts of reading must be updated to account for this variance in reading skills.

Introduction

The study of the cognitive underpinnings of literacy and reading skills has increasingly viewed reading acquisition as an exercise in statistical learning (SL). This perspective rests on an understanding that writing systems can be characterised in terms of systematic mappings between the orthographic, phonological, morphological, and semantic properties of words and their representations (Sawi & Rueckl, 2019). Accordingly, proficient reading has been demonstrated to rely on efficient mapping between units at these various levels of representation, across a variety of different languages and writing systems. This has led researchers to propose universal and cross-linguistic models of both reading processes (Frost, 2012; Seidenberg, 2011) and literacy acquisition (Arciuli, 2018; Treiman & Kessler, 2006).

More generally, SL has been studied as a potentially domain-general cognitive mechanism that undergirds all language learning. Statistical co-occurrences of syllables have been shown to support word-segmentation in infants, allowing them to recognise low-probability transitions as more likely to be word boundaries (Nazzi et al., 2006; Saffran, 2003). Individual differences in performance in simple abstract SL tasks have also been shown to predict reading skills in both first language (L1) readers (Arciuli & Simpson, 2012; Misyak & Christiansen, 2012) and second language (L2) learners (Frost et al., 2013). Although this literature does constitute evidence that individual differences in SL abilities are related to reading abilities, there are still many open questions about the mechanisms that underlie this relation. Not least that it is unclear how performance in abstract SL tasks performed in the laboratory setting extends to account for the rich multidimensional statistics that characterise real-world writing systems (see Erickson & Thiessen, 2015; Frost et al., 2019 for further review). Correlations between performance on SL tasks and measures of reading ability appear to depend on the specific tasks in question (Elleman et al., 2019; Lammertink et al., 2020), and to be quite varied in magnitude (Schmalz et al., 2019).

Although the SL account of reading is presented as a universal characteristic of reading processes, almost all of the research into both SL in general, and the SL account of reading processes in particular, has focused on what are termed WEIRD populations, that is people from Western, Educated, Industrialised, Rich, and Democratic countries (Henrich et al., 2010). This limits our ability to generalise our understanding of SL, both in general, and more narrowly in the context of reading, across additional understudied contexts and populations. A recent paper by Zinszer and colleagues (Zinszer et al., 2023), for example, showed that performance in a typical SL task does not directly translate across these sorts of socio-cultural borders without careful adaptation. This suggests that the existing theories regarding the relation between SL performance and reading skill, which build on typical SL tasks as examined in WEIRD contexts, may also not extend neatly to other populations.

The context in which literacy skills develop in non-WEIRD populations differs substantially, and in many ways, from that in WEIRD contexts. Crucially, fluent L1 literacy development has been shown to depend on a broad set of pre-existing domain-general and language skills that typically develop from early childhood (Storch & Whitehurst, 2002; see Snow, 2006 for review). However, the poverty endemic to low- and middle-income countries (LMICs, which account for some 80% of the world's population) can have a significant impact both on children's cognitive development (Jasińska et al., 2022; Obradović et al., 2016; Waber et al., 2014) and language exposure (Fernald et al., 2013), both of which likely affect their ability to build fluent reading skills. Therefore, understanding the underpinnings of literacy in more diverse contexts is crucial for a truly universal understanding of literacy.

The current study focuses on children in rural cocoa-growing communities in Côte d'Ivoire, who are acquiring literacy in French. Côte d'Ivoire (CIV) provides a clear example of the economic and social constraints experienced in non-WEIRD contexts, ranking 162nd out of 189 countries in the Human Development Index (UNDP, 2020), with a poverty rate of 29.8% (UNESCO Institute for Statistics, 2019), that in some rural communities rises to over 60% (Fonds Monetaire International, 2009). Less than half of adults over the age of 15 are literate, and, while school enrolment is over 90%, only 73% of children who start school make it to the last grade of primary, and only some 50% of children enrol in secondary education (UNESCO Institute for Statistics, 2019). There is high variability in the age at which children begin schooling, some starting at age four, but some as late as age 12, and school closures and absences are very common (Gulemetova et al., 2016). Thus the amount of exposure to written materials that Ivorian children in a rural context receive is significantly lower than would be typical in WEIRD contexts. The quality of education for literacy is also significantly lower than in most WEIRD contexts in terms of infrastructure, teacher training and teaching materials (Ball et al., 2023; Cannanure et al., 2022). While the most recent updates to reading instruction policies in the Ivorian curriculum incorporates a focus on phonics (Department of Pedagogy and Continuing Education, 2018), policies are often poorly implemented in the classroom, especially in the rural context. Anecdotally, our own research team has observed classroom reading instruction that focuses on the whole-word and rote repetition, with virtually no phonics-based instruction. This is further evidenced by the recent partnership of the Ivorian Ministry of National Education and Literacy with TaRL (Teaching at the Right Level; TaRL - Côte d'Ivoire, n.d.), an international NGO who support governments in designing and implementing educational programmes for foundational literacy and numeracy skills. TaRL are working with the Ivorian Ministry of

Education to provide teacher training and support, and educational methodologies to improve reading and mathematics skills, with the targeted reading instruction focusing on foundational decoding skills.

Children in rural CIV typically speak one or more of over sixty Ivorian languages as a first language, but are usually educated largely or solely in French, which for the majority is an L2 (Brou-Diallo, 2011; Jasińska & Guei, 2022), that they begin learning at school. Ivorian languages rarely appear in print, and French serves as the official national language and the prestige language for social, scholastic, and academic purposes. Children in rural CIV therefore typically have no exposure to print in their L1, and little-to-no exposure to their L2 prior to, or outside of, the school context. This means that the environment in which literacy acquisition occurs differs substantially from the typical WEIRD environment for either developing L1 readers or adult L2 learners. L1 literacy, in building a network for reading in the brain (e.g. Preston et al., 2016; Schlaggar & McCandliss, 2007), is typically an important basis on which L2 literacy skills are built both in terms of brain organisation (Brice, Frost, et al., 2021) and behaviour (Havron & Arnon, 2017). But the age of exposure to a second language also impacts the way that written language is processed (Jasinska & Petitto, 2013), with lexical-semantic aspects of the reading network playing a greater role, and phonological aspects a reduced role, in late-exposed bilinguals (Jasińska & Petitto, 2018). Specifically, bilingual children (6-10 years) who were first exposed to their second language at age 5 years showed a stronger reliance on lexical-semantics in reading relative to bilingual children exposed to two languages from birth and monolingual children. This is in line with evidence that phonological processing plays a greater role in language learning in younger children (Badian, 2001), while vocabulary and semantic learning continue to play a significant role at later stages of development (Newport, 1990). Children in CIV start literacy acquisition in their L2 without the prior literacy skills developed in their L1 that adult L2 learners in WEIRD contexts typically have, but without the fluency and familiarity with the spoken language that developing L1 learners can leverage. In the current study we examine the reliance of these emergent French readers in rural Côte d'Ivoire on the extraction and processing of statistical regularities inherent in the French writing system. This will allow us to examine whether the SL account of reading can account for reading skills across diverse populations and contexts.

Literacy acquisition and the leveraging of regularities

Recently, several studies have directly probed the mechanism by which SL impacts reading processes, demonstrating how the lexical and sublexical statistical characteristics of words impact how they are read (see e.g. Elleman et al., 2019). Individual differences in the extent to which readers are impacted by regularities in mapping orthography to phonology and semantics have been shown to predict reading skill in English in both developing L1 readers (Siegelman, Rueckl, et al., 2020), and adult L2 learners (Brice, Siegelman, et al., 2021). Siegelman et al. (2020) and Brice et al. (2021) both utilised a task designed to measure the impact of lexical and sublexical associations between orthography, phonology, and semantics on word naming performance. The task characterised words using three types of regularities known to impact word reading: (a) consistency of mapping from orthography to phonology (O-P); (b) the mapping from orthography to semantics (O-S; operationalised by a metric of imageability, see methods section); and (c) the frequency of words' appearance. These factors impact adult readers in English (Strain et al., 1995), with all three factors affecting word reading speed and accuracy. Siegelman et al. (2020) examined these individual differences in developing readers acquiring L1 literacy in English (N = 123, age 7.8-11.3), finding that stronger readers relied more on O-P associations, while weaker readers relied more on the semantic measure of imageability. In a second study with adult L2 learners of English (N = 38), that examined the longitudinal development of these sensitivities, Brice et al. (2021) found that they quickly begin to leverage the O-P regularities inherent in a new orthographic system, assimilating this novel statistical information for reading. However, sensitivity to imageability took more time to develop and was only evident after some years of L2 immersion. This was somewhat different from the results in child L1 readers, where semantic effects were visible even in beginner readers. This suggests that semantic associations rely on the development of spoken language fluency, and may therefore be less available for L2 readers who are learning the spoken language in parallel with the written.

For our current study, we adopted this methodological approach, and developed a novel word-naming task in French, designed to leverage similar lexical and sublexical characteristics, but accounting for differences between the English and French orthographies.

Focusing first on associations between orthography and phonology, French orthography differs substantially from English in terms of its (ir)regularity. In English, the primary source of irregularity is in the mapping from O to P, such that a consistent word like *beer* can only be read in one way, while an inconsistent word like *pint* could potentially be pronounced similarly to *mint* (although, see e.g. Siegelman, Kearns, et al., (2020) for discussion of P to O effects on reading accuracy and latency in English). In French, however, the mapping from O to P is highly consistent, and it is the mapping from P to O that is more highly variable (see supplementary data for an analysis), so that a consistent word such as *loin* ('far') is essentially the only possible orthographic and lexical representation of the phonological string \lwɛ̃\ (consistent O to P) , but the phonological string /sɑ̃/ could be orthographically represented by *sang* ('blood'), *cent* ('hundred'), *sens* ('I feel') or *sans* ('without') (inconsistent P to O). We therefore focused primarily on a measure of P-O consistency for the task design and the primary analyses, and kept a measure of O-P consistency as a secondary measure for analysis purposes, and to ensure that the focus on O-P was not the sole reason for any differences found in the current cohort compared to previous research.

O-S mappings allow readers to e.g. distinguish between homophones (e.g. *ring* and *wring* map onto different semantic concepts), but are typically most clearly reflected in morphological structure, such as shared lexical roots and affixes that can connect words despite phonological differences (e.g. *heal* and *health*). Although O-S regularities are less systematic than O-P mappings, both lexical and sublexical semantic regularities have been shown to be assimilated and leveraged by readers (Monaghan et al., 2017; Seidenberg & Gonnerman, 2000; Strain & Herdman, 1999). Given our focus on monosyllabic (and mono-morphemic) words, we could not utilise a measure based on morphological structure, which most directly showcases O-S mappings. To measure the impact of O-S processes, we therefore utilised a metric of imageability, or how easily the printed word leads to a mental image of the semantics (e.g. a concrete noun such as *dog* is more imageable than an abstract noun such as *truth*). While this does not constitute a direct measure of the mapping from the orthography to semantics, it is a very common proxy for the involvement of semantics in word reading tasks. Imageability is taken to reflect the impact of conceptual knowledge on word reading, which is a crucial aspect of O-S processes, and reflects the degree of intercorrelation of semantic and lexical features (Harm & Seidenberg, 2004; Rueckl, 2010). If more imageable words are being processed more efficiently, that indicates that lexical-semantic information, which depends on the strength of O-S associations, are playing a role in the reading process (Woollams et al., 2016).

Our final metric is word frequency, a distributional statistical characteristic, which is one of the primary factors in determining word reading speed and accuracy (Grainger, 1990; McRae et al., 1990). Frequency has been shown to be an important modulator in word naming, influencing the division of labour between phonological and semantic associations (e.g. Strain et al., 1995), with imageability supporting word naming performance primarily for infrequent and inconsistent words. Importantly, frequency has been shown to have a stronger impact on word naming latency and accuracy in less fluent adult readers, with fluent readers able to easily read words across the range of frequency, while poorer readers struggle with the more infrequent words (Kuperman & Van Dyke, 2011; Monaghan et al., 2017).

The current study

Our data was collected as part of a longitudinal study of literacy acquisition in eight villages in the greater Adzópe region of CIV. As part of the study, children participated in the French word naming task described below, measuring the impact of P-O regularities, imageability and frequency on word naming accuracy. In addition they completed a number of tasks measuring French literacy and language skills.

Our primary focus in this study was on the individual differences in sensitivity to the different statistical characteristics. We therefore estimated individual sensitivity to each measure, and examined the relative reliance of each individual on each one, how these individual differences are related to one another, and how they predict overall literacy skills. In developing L1 readers and adult L2 readers of English, we have seen that more proficient readers are better able to leverage more informative mappings, relying more on O-P consistency and less on imageability. Here we will examine whether L2 readers who are not literate in their L1 will show similar patterns of reliance on statistical regularities in their reading performance.

We thus have three primary research questions: First, (1) do emergent L2 French readers in rural Côte d'Ivoire leverage regularities in the mapping between orthography, phonology and semantics during word reading? We then turn to our investigations of individual differences, asking (2) whether we see an individual level trade-off in the leveraging of different sources of information, with readers who rely more on one source relying less on others. Finally, we examine (3) whether sensitivity to our sources of regularity substantially predicts reading skill.

We expect that at the group level, our readers' accuracy will be impacted by all three sources of regularity, however, the impacts of both P-O consistency and imageability may be small, given the relatively low reading skill of our cohort, and prior evidence that these sensitivities take time to develop in both L1 and L2 readers (Brice, Siegelman, et al., 2021). The group level results are crucial, as they will constitute proof that our item-level measures of regularity are appropriate measures, that tap into relevant variance in the interface between French orthography and phonology, and that our task is appropriate for measuring the impact of regularities on reading performance in French and in our cohort. We further expect to see a trade-off between individual reliance on P-O and imageability, as seen in the previous literature, with individuals who rely more on consistency showing less of an impact of imageability, and vice versa. Finally, although previous work has shown that individual differences in the leveraging of regularities significantly explain much of the variance in reading skill in both developing L1 and adult L2 readers, it is an open question whether the leveraging of regularities will play a similar role in emergent readers in non-WEIRD contexts. Given the theoretically universal nature of the statistical account of reading, it is important to understand how universally applicable it is in practice.

Methods

Participants

Our participants were recruited from a larger cohort involved in a longitudinal intervention project on literacy acquisition in rural CIV. A power analysis suggested that a sample of 116 participants would achieve power of $\alpha = 0.9$ to find even a small effect (total adjusted $R^2 = 0.15$) in predicting reading skills from individual sensitivity metrics. Given the magnitude of previous results, with R^2 of the individual differences model ranging from 0.24 to 0.54, as well as our estimate that a single researcher could test 15-20 children a day, a sufficient sample size was deemed achievable in the two-week data collection period. Our final sample size was determined by the data collected as part of the mid-line visit to schools in the control arm of the longitudinal study, totalling 180 children (97 female). Due to variance in school-starting age, and high incidence of grade repetition, ages at time of data completion ranged between 10 and 18 (μ = 12.74, SD = 1.31). Participants were initially enrolled in the study while in grade CM-1 (the equivalent of 5th grade), and were mostly in CM-2 (the equivalent of 6th grade) at the time of data collection. All participants were studying French in school, and 29% of participants reported having at least one French-speaking family member at home. 134 of the participants completed the word-naming task, with all other participants failing to complete the task due to no responses to the initial ten trials (93%) or due to experimenter error (7%).

The study was approved by the [name deleted to maintain the integrity of the review process] Research Ethics Board. Each community's local governing body (the village chief), the parent representative group (COGES), and school directors provided informed consent after presentations by the research team, in accordance with both local norms and institutional ethics considerations (Jasińska & Guei, 2018). Researchers obtained verbal assent from each child prior to beginning the study. Children were allowed to stop participation at any time, and received a small gift in return for their participation.

Design and Procedure

The design of the word-naming task at the focus of the current study was based on that used in Siegelman et al. (2020) and Brice et al. (2021), utilising French words and regularity metrics. The experiment was performed using PsychoPy2 (Peirce et al., 2019), data were collected by an Ivorian linguist who is also a native speaker of Ivorian French, and the study was carried out in Ivorian French. The test trials were preceded by two untimed training trials in each of which a single high-frequency and high-consistency word was presented on the screen. The experimenter asked the participants to read the word aloud in French quickly and accurately, and advanced to the second trial only once the participant had understood and complied. The task included 160 test trials, presented to subjects in a randomised order. In each trial, a fixation cross was presented for 1000ms, which was replaced by a monosyllabic French word presented in the centre of the screen in white on a dark grey background to minimise glare. The target word remained on the screen for 2500ms, until the fixation cross for the next trial came onto the screen. Participants were asked to read each word aloud as accurately and quickly as possible. Responses were marked for correctness using a form administered via REDcap, hosted at the University of Toronto (Harris et al., 2019). If the participant did not produce any response at all to the first 10 test trial words, the experimenter stopped the experiment.

Materials

Target words were monosyllabic French nouns and adjectives, chosen to vary along our three independent variables of interest: frequency, imageability and P-O regularity. Due to a paucity of corpus data for Ivorian French, our target words and measures were all taken from European French databases. However, all target words were validated for Ivorian French, and ratings were confirmed as reasonable for Ivorian French speakers by a local linguist and native Ivorian French speaker. Mean word length was 4.58 letters (range: 2-7). Log-transformed frequency was taken from the Manulex-infra corpus of child-directed written material (Peereman et al., 2007), and ranged between 0.31 and 893.91 per million words (mean 87.98) in first-grade equivalent metrics. First grade ratings were chosen to be the best approximation for the exposure of our French-L2 participants in a rural agricultural context to French writing, as, even for the more fluent readers, exposure to written French will be substantially lower, and less varied, than for developing readers in France. P-O and O-P consistency ratings were also taken from the Manulex-infra corpus, transformed to probability scores, and log-transformed to provide consistency scores. Mathematically, this score is the inverse of the information theoretical construct *surprisal*, or the extent to which the orthographic representation is unexpected given the pronunciation (see Siegelman, Kearns, et al., 2020). Because (ir)regularity in French orthography is driven by consonants as much as vowels, we chose the mean P-O and O-P token-consistency rating across the entire monosyllabic word (designated as COPGTTO and COGPTTO, accordingly, in the Manulex-infra corpus), rather than focusing on vowel consistency alone. Imageability ratings were taken from Desrocher & Thompson (2009). Items were selected to minimise correlations between our three primary variables. Correlations between the three variables were small (frequency and P-O consistency: $r = 0.085$; frequency and imageability: 0.010; imageability and P-O consistency: -0.037). P-O and O-P consistency were more highly correlated with one another ($r = 0.287$, $p < 0.001$), which is not surprising given the inherent interrelation between the consistency of mappings between orthography and phonology.

This correlation should however be kept in mind when considering the results of our analyses.

An attempt was made to collect response time measures for this task, however the limitations of data collection in an outdoor rural schoolyard setting provided audio recordings that were too noisy for reliable response times to be collected. We therefore report only accuracy measures.

In addition to this primary task, a series of tasks measuring French phonological awareness, vocabulary, oral language comprehension, and literacy skill were collected as part of the study, that we utilise here to provide a metric of literacy and spoken language skills. Native speakers of Ivorian French collected all data.

Phonological awareness

Phonological awareness was assessed using 10 trials each of initial phoneme identification, initial phoneme deletion, final phoneme deletion and phoneme segmentation. These were taken from the Early Grade Reading Assessment (EGRA; Gove & Wetterberg, 2011; RTI International, 2009), Yopp-Singer segmentation task (Yopp, 1995), and the phoneme deletion task (Bruce, 1964).

Vocabulary

Vocabulary was assessed with the synonym and antonym subtasks from the French edition of the Woodcock-Johnson-III Test of Cognitive Abilities (Woodcock et al., 2001), in which children were asked to provide a synonym (e.g. prompt: *regarder* ‘look’, response: *voir* ‘see’) or an antonym (e.g. prompt: *froid* ‘cold’, response: *chaud* ‘hot’). Ten prompts were provided for each task.

Oral language comprehension

Oral language comprehension was assessed with the EGRA, in which a short story was read aloud twice by the experimenter, after which the child responded to five open questions.

EGRA literacy task

In addition, participants completed a series of timed French reading tasks taken from EGRA (RTI International, 2009): (1) a grapheme reading test, in which participants were asked to sound out 100 French graphemes and grapheme clusters (e.g. *e*, *un* or *ch*); if no correct answers were provided for the first ten graphemes, the task was stopped and a score of 0 was given; (2) word and pseudoword reading tasks, in which children were tasked with reading as many of a list of 50 French words (e.g. *lire* or *ami*) or pseudowords (e.g. *mouli* or *bape*) as they could in 60 seconds for each task. These measures have been previously utilised in Côte d'Ivoire, and have been found to be both reliable and valid in this population (Sobers et al., 2023).

Results

Literacy and language tasks

Mean performance on the language and literacy tasks ranged between 42% and 84.4%. All tasks showed a broad range of individual results, and all tasks showed high internal reliability (all > 0.85), with the exception of the Oral Comprehension task, which constitutes only 5 items. For full results and measures of reliability see Table 1. Each set of tasks was converted to a composite index variable, utilising the method described in Anderson (2008), which has been previously utilised in randomised control intervention projects in both the US (Anderson, 2008) & Kenya (Haushofer & Shapiro, 2016). This method converts each measurement to a z-score, and the index is then estimated as the weighted average of these scores, with the weight determined by the inverse of the covariance matrix of the transformed measures. The reliability of the composite scores as reflected by Cronbach's α was high for both composites.

Table 1

Performance on language and literacy tasks

		Mean accuracy % (SD)	% Range	% Zero scores	Split half reliability	Cronbach's α
Literacy Tasks	Grapheme Identification	61.1% (18.1)	9 - 100%	0%	0.857	
	Word Reading	52.5.4% (21.3)	0 - 83%	1.7%	0.885	0.920
	Pseudoword Reading	42.3% (20.0)	0 - 83%	3.4%	0.895	
Language Tasks	Phoneme Identification	71.9% (16.7)	27.5 - 100%	0%	0.949	
	Vocabulary	52.6% (16.6)	15 - 90%	0%	0.929	0.849
	Oral Comprehension	84.4% (20.7)	20 - 100%	0%	0.613	

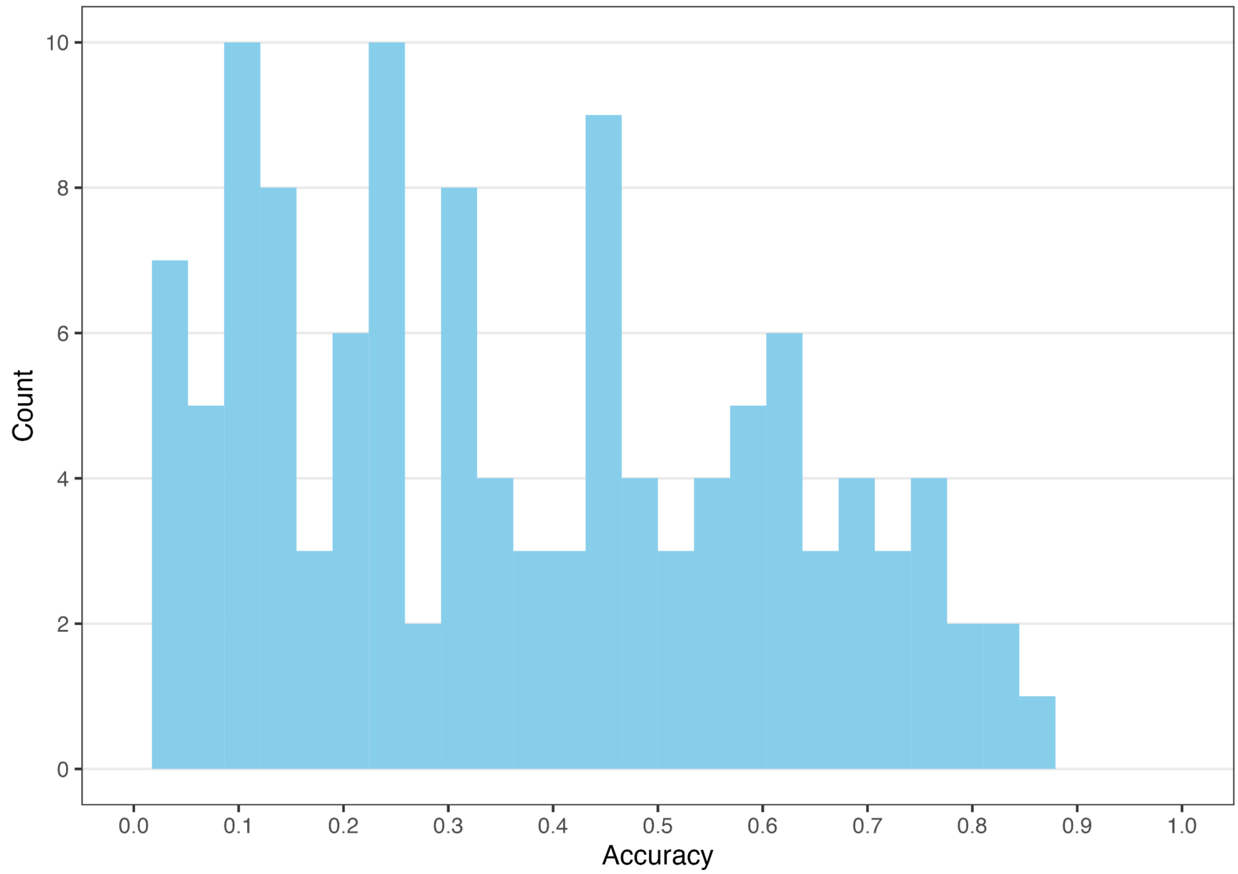
Note: Measures are provided for the final sample who completed the word naming task.

Group-level Results

We first analyse the group-level results of the word-naming task. Overall accuracy on the word-naming task in our final sample was relatively low (37.1%, SD = 23.5), but showed a broad spread (range: 2.5-87.5%). This was expected given that the stimuli included both highly infrequent and highly inconsistent words, but it should be noted that this is somewhat lower than has been seen in previous studies. See Fig. 1 for the distribution of accuracy

Figure 1

Histogram of naming accuracy in the word naming task



Note: Data for the final sample only.

We used the *lme4* package in R (Bates et al., 2015) to run a mixed-effect logistic regression (Jaeger, 2008) to model trial-level accuracy results, with correct responses coded as 1, and incorrect or no responses as 0. The model included our measures of frequency, imageability and P-O consistency, all scaled and mean-centred to reduce collinearity. The maximal random effects model that converged (Barr et al., 2013) included by-subject random intercepts and random slopes for frequency.

Table 2 shows results for the group-level model. Frequency and P-O consistency had the predicted effects. More frequent and more consistent words were named more accurately. Frequency and consistency showed a similar sub-additive interaction to that seen in L1 readers

(Siegelman, Rueckl, et al., 2020) and adult L2 readers (Brice, Siegelman, et al., 2021), with the effect of P-O consistency being greater for infrequent words. The three-way interaction shows that the interaction between frequency and consistency was stronger for words with lower imageability. We discuss the patterns of interaction in the general discussion.

Table 2
Group-level fixed effects on accuracy in word naming task

Predictor	β	SE	z value	p value
Frequency	**0.191**	**0.018**	**10.903**	**< 0.001**
Consistency	**0.181**	**0.018**	**9.914**	**< 0.001**
Imageability	-0.005	0.017	0.256	0.773
Freq. * Cons.	**-0.087**	**0.020**	**-4.235**	**< 0.001**
Freq. * Image.	0.020	0.017	1.162	0.245
Cons. * Image.	-0.011	0.019	-0.561	0.575
Freq. * Cons. * Image	**-0.066**	**0.021**	**-2.997**	**0.002**

Note: Significant effects in bold

Individual Differences Analysis

To estimate individual differences in the sensitivity to regularities, and to examine the impact of these individual differences on L2 literacy skills, we ran a set of logistic regression models for each of our dependent variables for each subject individually. Each model had trial-level accuracy for a single participant as the dependent variable, and a single by-trial variable of interest (frequency, imageability, P-O consistency, or O-P consistency) as the independent variable. The output of each model provides us with an individual slope for that variable, estimating the extent to which that individual was impacted by that variable. Because our individual-level models predict accuracy, at least some correct responses are necessary (no slopes can be estimated if all trials are incorrect). We therefore excluded from the individual-level analysis any participant with less than 2% accuracy. This left us with data for 119 participants, all of whom are included in the following analyses.

Measures of individual sensitivity to frequency, O-P consistency and P-O consistency were all significantly greater than zero on average, but sensitivity to imageability was not. Table 3 shows the descriptive statistics for each of our measures of sensitivity. For full correlation tables of all sub-task measures, see supplementary data.

Table 3
Descriptive statistics of individual slopes for sensitivity to regularities.

	μ	SD	t value	p value
Frequency	**0.241**	**0.241**	**10.845**	**< 0.001**
Imageability	-0.024	0.201	-1.281	0.203
P-O consistency	**0.241**	**0.214**	**16.374**	**< 0.001**
O-P consistency	**0.359**	**0.238**	**12.209**	**< 0.001**

Note: Mean scores significantly greater than zero in bold.

We next examined the correlations between individual sensitivity to the different measures of regularity, to examine any trade off in sensitivity to the different metrics. None of the sensitivity measures directly correlated with one another. Language and literacy composite scores were significantly correlated, and sensitivity to imageability was correlated with literacy scores. See Table 4 for the complete correlation matrix. Full correlations of all tasks and measures can be found in the supplementary data, but correlations with the literacy and language sub-tasks showed a very similar pattern to those seen with the composite scores.

Table 4
Bi-variate Pearson correlations of individual sensitivity to our measures of interest.

	Frequency	Imageability	P-O Cons.	O-P Cons.	Literacy	Language
Frequency	-	0.084	0.120	0.111	-0.096	0.125-
Imageability	1.00	-	-0.183	0.188	**0.279**	-0.048
P-O Cons.	1.00	0.562	-	0.127	-0.088	-0.054
O-P Cons.	1.00	0.532	1.00	-	-0.051	0.035
Literacy	1.00	**0.032**	1.00	1.00	-	**0.434**
Language	1.00	1.00	1.00	1.00	**<0.001**	

Note: Significant correlations ($p < 0.05$) are shown in bold. Upper triangle contains correlation coefficients, lower triangle contains Holm-corrected p-values.

Finally, we turn to our third avenue of investigation, predicting literacy skills from individual differences in sensitivity to regularities. We first ran a model based on Brice et al. (2021), predicting literacy scores from individual measures of sensitivity to our three metrics, and the interaction between imageability and P-O sensitivity in order to test a trade-off between reliance on imageability and P-O sensitivity. All measures were scaled and mean centred. Only imageability significantly predicted literacy skills, and no trade-off was seen between reliance on imageability and consistency. Additionally, this model explained only 7.4% of the total variance in literacy skills. See Table 5 for the full results.

Table 5
Regression model predicting reading skill from individual differences in sensitivity to P-O consistency, imageability, frequency.

R^2_{Adj} = 0.0738	β	SE	t Value	p Value
Frequency	-0.126	0.091	-1.392	0.167

Imageability	**0.254**	**0.095**	**2.682**	**0.008**
P-O Consistency	0.021	0.099	0.208	0.835
Imageability * Consistency	0.106	0.085	1.242	0.217

Note: Significant predictors in bold.

Given the high correlation between French language and literacy scores, we further examined the impact of adding overall French language skills to the model, including the interactions between language skills and the measures of sensitivity. To this end, we ran a multiple regression model predicting literacy scores from individual measures of sensitivity to our three metrics and our composite French language score. We found that both language skills and sensitivity to imageability significantly predicted literacy skills, with stronger readers being more sensitive to imageability. However, the relation between language skill and literacy also showed a marginally significant interaction with P-O sensitivity, with the extent of sensitivity to P-O consistency attenuating the relation between language and literacy skills. This interaction is further discussed below. The full model, including our measure of general French language skills, explained 23.39% of the variance in literacy skill. Model comparison utilising a chi-square test showed that this model was a significantly better fit for the data than the model without French Language skills (F(11) = 3.127, p = 0.001). See Table 6 for the full results.

Table 6
Regression model predicting reading skill from individual differences in sensitivity to P-O, imageability, frequency and French language skill

R^2_{Adj} = 0.2339	β	SE	t Value	p Value
Freq.	-0.067	0.100	-0.668	0.506
Img.	**0.282**	**0.092**	**3.077**	**0.003**
Con.	0.002	0.101	0.023	0.981
Lang.	**0.414**	**0.105**	**3.942**	**<0.001**

Freq. * Img.	0.141	0.129	1.096	0.276
Freq. * Con.	0.051	0.097	0.528	0.598
Img. * Con.	0.047	0.091	0.520	0.604
Freq. * Lang.	0.200	0.122	1.631	0.106
Img. * Lang.	-0.087	0.129	-0.675	0.501
Con. * Lang.	*-0.186*	*0.097*	*-1.193*	*0.058*
Freq. * Img. * Con.	0.045	0.132	0.339	0.735
Freq. * Img. * Lang.	-0.027	0.128	-0.213	0.832
Freq. * Con. * Lang.	-0.006	0.081	-0.070	0.944
Img. * Con. * Lang.	-0.098	0.103	-0.962	0.338
Freq. * Img. * Con. * Lang.	0.143	0.116	1.232	0.221

Note: Significant predictors in bold, marginal in italics. Freq = sensitivity to frequency; Img. = sensitivity to imageability; Con. = sensitivity to consistency, Lang. = French language composite score.

Discussion

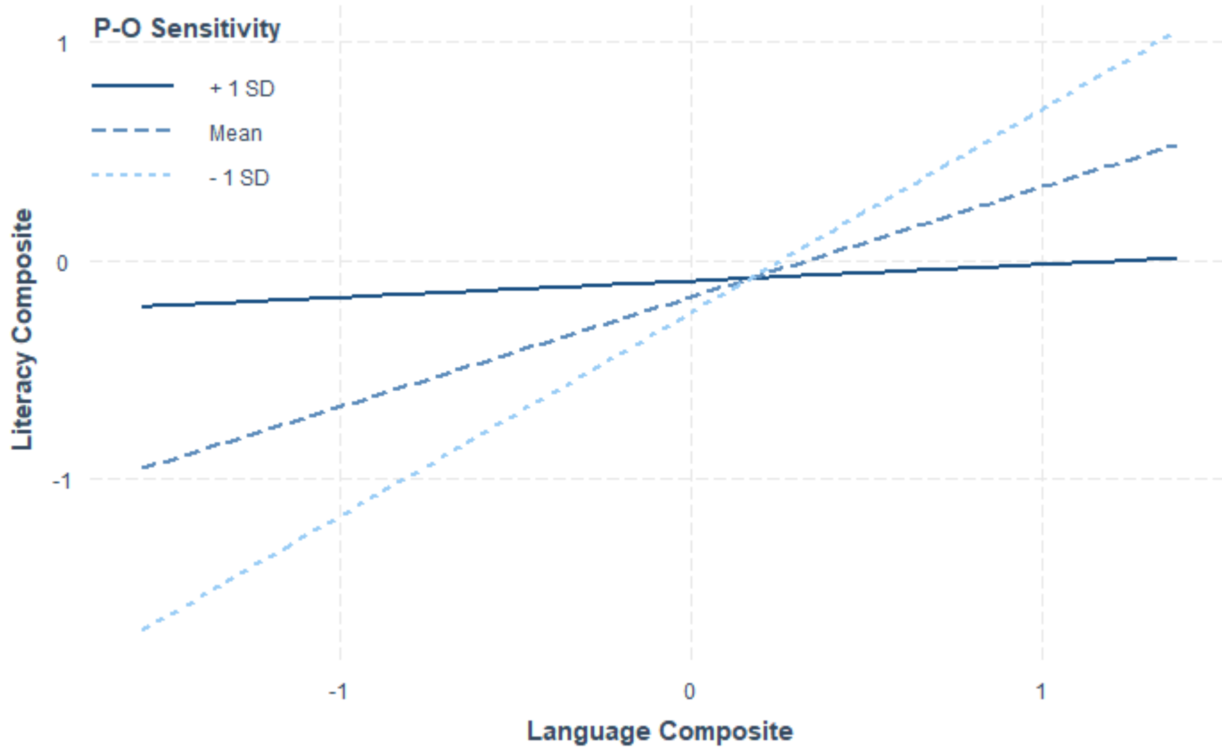
In this study, we examined (1) whether emergent readers in rural Côte d'Ivoire leverage regularities in reading, (2) whether they show a trade-off between sensitivity to consistency and imageability, and (3) whether individual differences in leveraging regularities predicts reading skill. We found first that, at the group level, regularities played a very similar role for our readers as was seen in both emergent L1 readers and in adult L2 learners in the US. Namely, both frequency and consistency directly aided naming accuracy, with consistency more important for infrequent words. Similar to previous findings, imageability did not have a main effect on reading, but interacted with frequency and consistency, such that consistency was most heavily relied upon for infrequent and less imaginable words. The group level results are important for our interpretation of the individual differences, as they show that our metrics are picking up on facets of information that readers of French are sensitive to, and thus influence reading behaviour at the group level. This confirms the relevance of our metrics for probing sensitivity to these characteristics in French reading and in our cohort.

However, individual sensitivity to our three primary factors, namely frequency, P-O consistency, and imageability, showed a very different pattern from that seen in previous studies. First, no significant tradeoff was seen between reliance on imageability and P-O consistency, as has been seen in both developing L1 (Siegelman, Rueckl, et al., 2020) and adult L2 readers (Brice, Siegelman, et al., 2021) in English. Individual measures of sensitivity were not related to each other, and readers did not show evidence that they relied more on one source of information or the other.

In previous studies, stronger readers showed less sensitivity to frequency and imageability, and a greater sensitivity to consistency (Brice, Siegelman, et al., 2021; Siegelman, Rueckl, et al., 2020). In the current study, only imageability was a significant predictor of reading skill, and it was opposite in effect, with stronger readers showing a greater impact of imageability on their word naming performance. This is despite the fact that, at the group level, significant sensitivity was seen to both frequency and consistency.

A marginal interaction was seen, however, between P-O consistency and overall language skills as the basis for reading skills. This suggests that although children who had better French language skills were also better French readers, those who were more sensitive to regularities in the mapping from phonology to orthography were somewhat less dependent on French fluency to read words accurately (see Fig. 2). In other words, good sensitivity to P-O regularities could potentially help readers achieve decent reading skills even when they were not fluent in French. However, this effect was only marginal, and further investigation is merited before any strong conclusions can be drawn.

Figure 2
Interaction between language skills and P-O sensitivity in their impact on literacy skills.



Note: Plot created with the interact_plot() function in the interactions package for R (Long, 2021).

The lack of a first-order impact of sensitivity to frequency or P-O regularities on reading skill is possibly due to the relatively low reading skill in our cohort, who had a mean naming accuracy rate of 33%, as compared to 69% in the L1 cohort (Siegelman, Rueckl, et al., 2020) and over 90% in the L2 cohort (Brice, Siegelman, et al., 2021). Group effects show that P-O & O-P regularities, as well as frequency statistics, do impact word naming at the group level, meaning that our participants have assimilated these structural regularities in mapping. It is possible that fluency may not be sufficiently high in our cohort to show differences in the direct impact of this sensitivity at the individual level. However, such an explanation seems somewhat insufficient, in that individual sensitivity to regularities has previously been shown to be predictive of reading skill across a very broad spectrum of ability. Siegelman and colleagues (2020) included both typically developing readers and those with diagnosed reading disabilities, and Brice and colleagues (2021) examined L2 readers both shortly after beginning L2 literacy acquisition and two years later when fluency was far greater. In our Ivorian cohort, while some participants showed very low accuracy, the upper bound of the range of literacy and language skills was at or near ceiling. Although our data do not allow us to speak directly to the cause of the differences, the lack of effect could potentially be due to several other factors impacting reading skills in our cohort.

First, age of first exposure to an L2 (Jasinska & Petitto, 2013), as well as L2 proficiency (Perani, 1998), have been shown to significantly impact the organisation of the neural systems that support written language processing. Therefore, for our cohort, who mostly began acquiring French relatively late and as an L2, the underlying neural architecture is likely somewhat different from that underlying developing L1 readers or L2 learners in WEIRD contexts. Furthermore, it has been shown that adult L2 learners who are literate in their L1 rely on their pre-existing L1 reading network to develop their L2 reading skills (Brice, Frost, et al., 2021). Our cohort is different from typical L2 learners in WEIRD contexts, as they have no underlying L1 reading network on which to build. Thus, our emergent readers approach the task of L2 literacy acquisition in an atypical manner in terms of prior functional brain organisation. Furthermore, our readers also begin the task of acquiring reading skills at a later age than typical for readers in WEIRD contexts, with some students only beginning their education at age 10 or even 12 (Gulemetova et al., 2016). Development and experience change the brain's physical structure and functional organisation, meaning that readers who start acquiring literacy at a later age may have missed a "sensitive period" (Knudsen, 2004) in brain development, leading to the development of a reading network that is atypical compared to WEIRD readers who start literacy acquisition at age 5 or 6. The extraction and leveraging of regularities may therefore play a different role for our readers than has been seen in previous cohorts, meaning that the statistical account of reading must account for both the age and underlying language skills at the time of reading acquisition.

Finally, the regularities in mapping in French may play a slightly different role from that in English, or more specifically, a somewhat different role given the nature of the word naming task we utilised. A word naming task demands mapping from the orthographic input to a phonological output (O-P). O-P regularities are therefore more directly task relevant than the reverse P-O regularities, which map a phonological input to an orthographic output, even though P-O regularities are known to play an important role in word processing in French (Barca et al., 2017; Ziegler et al., 1996). It should also be noted, however, that both O-P and P-O have been shown to have significant and distinct contributions to naming behaviour even in English (Siegelman, Kearns, et al., 2020), so an effect of P-O should be expected in French, where it shows far greater inconsistency. It is important also to note that the impact of O-P consistencies were analysed utilising the same models reported here (see supplementary data for full report of the results), and showed essentially identical results. We did lack statistical power to directly contrast the impact of O-P and P-O regularities on reading skill within a single model, or to test any higher-order interactions, not least because of the correlation between O-P and P-O metrics leading to collinearity. It is possible that higher-order effects involving both O-P and P-O could be seen in a sufficiently powered sample (as have been reported on large scale database analyses in English, see Siegelman, Kearns, et al., 2020). Future studies of the impact of these regularities on L1 French readers, or L2 French readers in WEIRD contexts, can potentially address this possibility.

The significant positive relation between sensitivity to imageability and reading skill is also opposite from previous findings in English, where better readers showed less sensitivity to imageability. This result suggests that semantic processing may be playing a different role in literacy in this cohort compared to previous studies. As we saw, children in Côte d'Ivoire start school, and are first exposed to French, and to reading, at a later age than typical in WEIRD contexts. In combination with evidence from the literature that semantic processing plays a greater role in language processing as development progresses (Newport, 1990), and that semantic processing takes precedence over phonological for later exposed (>5 year old) bilinguals (Jasińska & Petitto, 2018), it is probable that our cohort rely more on semantic processing for reading than children acquiring literacy in WEIRD contexts.

It should be noted, however, that adult L2 learners in WEIRD contexts were slow to show an impact of semantic processes on reading performance (Brice, Siegelman, et al., 2021). This suggests that our L2 learners of French, with substantially less exposure to French than to their L1, may lack sufficient exposure to fully assimilate O-S regularities. This is commensurate with the fact that, while individual sensitivity to imageability was significantly correlated with literacy skill, it did not show a significant group-level impact on word naming accuracy, and the mean impact of imageability across subjects was not significantly greater than zero. This suggests significant variance in the participants' ability to leverage semantic processing.

The educational context in Côte d'Ivoire may also play a role in the lack of relation between sensitivity to consistency and reading skills. As described in the introduction, reading instruction in rural schools in Côte d'Ivoire often focuses on whole-word reading, and rote-repetition techniques, rather than utilising phonics-based instruction as is more common in WEIRD contexts. This means that children in our cohort are often not explicitly exposed to the alphabetic principle, and may thus be less aware of, and thus less primed to leverage, the mappings between orthography and phonology. No less important, children in Côte d'Ivoire have far less experience with written language on a daily basis than is common in the global North, meaning that the statistical basis of these mappings may not be robust enough in this cohort to be leveraged for reading at the individual level.

This paper underlines the need for further investigation of the relation between SL and literacy in broader cultural and socio-economic contexts. We have shown that the extraction and leveraging of regularities in reading plays a different underlying role in literacy across the spectrum of reading ability and cultural and educational borders. While sensitivity to regularities explained over 40% of variance in reading skill in developing L1 readers (Siegelman, Rueckl, et al., 2020), and over 50% of variance in fluent adult L2 readers (Brice, Siegelman, et al., 2021), only about 7% of variance in reading skill was directly explained by sensitivity to regularities in our cohort. This shows that individual differences in these regularities do not play the same substantial role that they have shown in previous studies. Although the cohort, language and task differences in the current study leave more than one possible explanation for these differences open, they are an important qualification to attempts to provide a universal SL theory of literacy.

Alongside the need for more investigation of the statistical aspects of literacy, our study shows that further study into cross-linguistic aspects of regularity is needed. Our group results suggest that P-O consistency plays a role for French readers not entirely unlike O-P for readers of English; however, further study to see if French readers in WEIRD contexts show a pattern more like that seen here is needed. This would allow us both to examine the test-retest reliability of our individual level measures of sensitivity, and whether SL processes play a lesser role in French reading than in English, or whether e.g. educational differences between populations explain the difference. More generally, sensitivity to a given facet of regularity may be not only language-, but task-dependent, with more effective statistical learners able to leverage the most informative regularities for the specific task at hand. Examination of both further facets of regularity and more cross-linguistic contexts will allow us to better answer these questions, and allow the statistical account of reading to provide a more comprehensive and universal framework for understanding reading processes, accounting for the impact of language-specific factors, and educational, maturational and exposure-driven factors that impact the leveraging of regularities in reading.

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Appendix I

Target items and metrics for word naming task

Target	Freq.	P-O	Image.	Target	Freq.	P-O	Image.
aide	110.72	46.95	2.95	lionne	0.61	66.29	6.63
ail	8.26	84.84	6.34	loin	519.38	100.00	3.76
aile	63.96	37.73	6.32	loup	516.75	66.53	6.88
balle	168.07	65.97	6.61	lune	0.35	80.92	6.87
banque	3.91	58.95	5.88	masse	0.50	68.02	4.04
basse	0.52	64.43	3.19	miel	147.40	86.76	6.50
bec	220.11	85.03	6.26	mode	13.02	83.75	3.34
biche	13.26	83.78	5.05	moi	5.48	99.99	4.59
blanc	297.43	59.56	5.76	mort	1.22	80.14	4.25
bombe	3.86	62.86	5.95	mot	238.60	55.69	4.37
bon	661.22	98.99	2.91	mouche	32.52	83.72	6.67
bonne	893.91	61.38	2.93	mouette	0.31	61.24	5.93
bouche	0.52	83.72	6.75	mur	195.94	99.32	6.08
bouge	86.29	78.40	3.33	nage	3.96	78.69	5.08
bout	3.86	75.16	4.19	nain	50.56	58.82	5.69
brique	7.97	72.76	6.72	natte	32.53	61.57	4.18
brosse	74.45	73.20	6.25	nu	42.08	99.96	5.37
bruit	414.79	84.11	3.36	nuage	73.82	82.95	6.74
côte	36.78	48.70	5.11	nue	1.05	78.02	5.09
cale	0.50	66.15	2.31	oeil	163.74	67.17	6.87
cane	1.19	70.51	5.75	or	41.79	95.46	5.97
cause	88.68	55.19	2.19	paille	0.505	58.83	6.40
cave	94.61	73.10	5.69	pain	331.26	58.82	6.77
châle	2.27	55.61	4.97	pape	0.42	80.64	6.23

chance	64.05	56.72	2.63
chauve	3.90	67.76	5.87
chien	784.49	75.70	6.97
choc	32.47	97.44	3.75
choeur	13.31	35.90	4.65
chose	202.75	67.38	3.26
ciel	231.89	64.46	6.69
clé	126.59	53.77	6.63
clef	0.61	34.69	6.28
clou	70.22	76.05	6.47
compte	78.81	40.04	3.08
conte	55.10	66.60	4.04
corps	75.70	56.93	6.04
cou	169.06	77.99	6.59
coude	21.97	72.77	6.38
coupe	127.35	69.44	5.15
crâne	1.21	58.25	6.62
crêpe	16.27	55.76	6.52
crainte	13.48	59.60	3.00
cuir	32.61	88.84	5.90
dé	21.62	66.40	6.30
dent	128.70	50.73	6.77
dinde	15.56	67.09	6.64
dix	176.78	68.71	5.15
doigt	71.97	56.29	6.92
douche	8.25	83.72	6.66
douze	73.08	60.24	4.97
patte	331.43	61.57	6.09
peigne	0.53	59.34	6.75
peine	0.62	56.75	4.11
piège	24.80	62.06	4.61
place	89.75	66.66	3.53
pleurs	0.52	77.81	4.66
plomb	5.42	46.88	4.93
pluie	293.88	81.46	6.31
plume	3.81	77.59	6.76
pointe	65.75	81.27	4.69
pomme	465.49	63.36	7.00
porc	3.90	73.52	6.61
pose	162.29	67.42	3.11
pou	4.03	99.82	4.98
prix	98.36	74.10	3.94
quille	32.99	49.63	6.59
rail	8.25	95.22	5.77
rame	28.11	79.44	6.26
rat	460.21	75.55	6.80
rires	2.09	72.47	4.51
roche	0.62	83.79	6.35
rose	83.51	67.42	6.91
roue	113.84	78.30	6.60
sang	16.44	51.15	6.62
saule	8.35	57.72	4.79
scie	12.57	45.07	6.53
sein	0.61	44.71	6.33

droit	19.10	79.83	3.48	sel	154.47	82.84	6.42
faille	0.52	61.34	3.76	sens	15.26	68.58	2.86
faim	167.93	48.58	3.62	serre	3.95	47.59	5.13
faute	50.31	64.08	3.27	singe	62.87	58.67	6.91
fil	259.56	98.05	5.66	six	151.99	64.53	5.22
film	72.62	91.73	6.11	soif	85.63	95.09	3.84
fils	82.13	71.94	5.20	son	40.89	92.72	3.26
flèche	5.56	62.70	6.64	songe	3.96	71.71	2.44
flaque	43.42	67.56	5.39	stade	4.04	82.55	4.70
fleuve	32.93	78.93	6.22	tache	50.13	83.84	4.91
flic	3.73	90.09	4.79	tante	78.55	72.66	5.41
foire	47.26	81.11	4.69	tas	52.30	72.10	3.81
fouille	23.07	61.05	3.72	tente	55.38	62.57	6.19
four	101.63	98.17	6.61	tige	19.44	78.28	5.94
gare	147.84	80.85	5.60	toc	83.51	97.26	1.60
globe	0.43	79.96	5.94	ton	441.74	98.64	3.38
goût	21.13	39.91	3.15	toux	0.35	66.88	4.61
grange	1.22	73.60	6.18	traite	0.61	68.14	2.55
griffe	0.62	68.75	5.84	tronc	21.73	69.72	6.21
grotte	21.87	66.53	6.02	trousse	50.59	73.00	4.95
groupe	5.45	81.75	4.62	truc	8.36	96.39	2.51
grue	28.60	80.35	5.11	tube	31.64	83.34	6.28
hâte	10.65	59.90	2.88	vase	81.74	78.66	4.57
honte	4.03	77.45	2.98	ver	45.66	99.86	5.70
jambe	81.91	58.48	6.72	viande	40.47	77.50	6.18
joueur	36.54	95.77	5.16	vie	126.38	78.28	3.22
joueuse	0.52	83.72	4.26	voile	53.18	76.45	6.25

lame	25.70	79.44	6.14	voix	257.81	67.42	3.94
lampe	138.13	56.58	6.77	vue	13.47	77.92	4.23