Cognition 262 (2025) 106172

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

The true colors of reading: Literacy enhances lexical-semantic processing in rapid automatized and discrete object naming

Susana Araújo [a,*], Tânia Fernandes [a], Margarida Cipriano [a], Laura Mealha [a], Catarina Silva-Nunes [a], Falk Huettig [a,b,c]

[a] Faculty of Psychology, Universidade de Lisboa, Lisbon, Portugal
[b] Max Planck Institute for Psycholinguistics, Nijmegen, The Netherlands
[c] University of Kaiserslautern-Landau, Kaiserslautern, Germany

ARTICLE INFO

Keywords:
Literacy
Object naming
Color naming
Lexical-semantic representations
Conceptual knowledge

ABSTRACT

Semantic knowledge is a defining property of human cognition, profoundly influenced by cultural experiences. In this study, we investigated whether literacy enhances lexical-semantic processing independently of schooling. Three groups of neurotypical adults - unschooled illiterates, unschooled ex-illiterates, and schooled literates - from the same residential and socioeconomic background in Portugal were tested on serial rapid automatized naming (RAN) and on discrete naming of everyday objects (concrete concepts) and basic color patches (abstract concepts). The performance of readers, whether schooled literate or unschooled ex-illiterate, was not affected by stimulus category, whereas illiterates were much slower on color than object naming, irrespective of task. This naming advantage promoted by literacy was not significantly mediated by vocabulary size. We conclude that literacy per se, regardless of schooling, contributes to faster naming of depicted concepts, particularly those of more abstract categories. Our findings provide further evidence that literacy influences cognition beyond the mere accumulation of knowledge: Literacy enhances the quality and efficiency of lexical-semantic representations and processing.

1. Introduction

Cultural acquisitions can dramatically transform the human brain and mind. A prime example of the power of such acculturation are the effects of *literacy*, that is, learning to read and write (for a review, see Dehaene et al., 2015; Huettig & Hulstijn, 2024). Literacy acquisition reconfigures neural networks (Carreiras et al., 2009; Dehaene et al., 2010; Dehaene-Lambertz et al., 2018; Hervais-Adelman et al., 2019; Skeide et al., 2017) and changes many perceptual and cognitive processes outside the written domain, such as the prediction of spoken language (Huettig & Pickering, 2019), verbal short-term memory (Demoulin & Kolinsky, 2015; Smalle et al., 2019), visual object recognition (Kolinsky & Fernandes, 2014) including face recognition (Van Paridon et al., 2021), orientation discrimination (Fernandes et al., 2021; Kolinsky et al., 2011), and visual search (Olivers et al., 2014). Thus, literacy serves as an ecological model for investigating how cultural experiences shape human cognition. Even among proficient readers, sustained reading practice appears to strengthen brain connectivity (Berns et al., 2013) and holds promise for countering (or at least delaying) cognitive decline associated with aging (Stine-Morrow et al., 2022).

The specific effects of literacy and schooling, while controlling for age and maturational confounds, can be empirically examined through quasi-experimental designs comparing literate adults with neurotypical *unschooled illiterate* individuals. These completely illiterate adults have not attended school and have never learned to read, strictly due to socioeconomic and cultural factors. For example, poverty and gender inequalities in access to formal education remain significant barriers in many countries and ethnic groups worldwide, such as the Dalit community in India or the Roma community in Portugal. Studying such populations thus provides a unique window into the culturally shaped mind.

It is important to distinguish between primary and secondary effects of reading (Huettig & Hulstijn, 2024; Huettig & Pickering, 2019). *Primary* effects are those directly linked to the cognitive processes of reading (e.g., the recognition of the particular shapes of the written

* Corresponding author at: Faculdade de Psicologia, Universidade de Lisboa, Alameda da Universidade, 1649-013 Lisboa, Portugal.
E-mail address: smaraujo@psicologia.ulisboa.pt (S. Araújo).

https://doi.org/10.1016/j.cognition.2025.106172
Received 29 May 2024; Received in revised form 8 April 2025; Accepted 30 April 2025
Available online 7 May 2025
0010-0277/

characters of writing systems, Fernandes et al., 2021; Kolinsky et al., 2011) or the specific type of eye movements that are induced by learning to read (Skeide et al., 2017). *Secondary* effects are those that can *also* be acquired indirectly through exposure to 'book language', as happens when listening to audio books or literary podcasts. For instance, listening to the audio version of James Joyce's Ulysses exposes listeners to sophisticated vocabulary (including subtleties of meaning) and syntactic constructions, albeit it does not directly involve the physical activity of reading.

In the present study, we investigated the potential impact of literacy on lexical-semantic processes and representations in two different naming tasks. This is an important question for cognitive sciences with societal implications, as semantic knowledge stands as a cornerstone of human cognition (e.g., Fernandino et al., 2022). It is thus surprising that despite the widespread effects of literacy on individual minds, its potential impact on the precision, richness, and strength of semantic representations has largely been overlooked. One reason for this oversight may be that the same mechanisms of access to and of hierarchical organization of semantic knowledge are typically assumed to be engaged in nonreaders and readers (Kolinsky et al., 2014; Kosmidis et al., 2004). For example, in *semantic* fluency, when participants produced as many items as possible from a semantic category (e.g., animals) in 1-min, illiterates displayed similar taxonomic clustering and retrieval by subcategory as literate people (Kolinsky et al., 2014).

Nonetheless, in the first large-scale investigation of the effects of literacy on semantic processing conducted in rural Uzbekistan, where nearly the entire population was completely illiterate at the time of testing in the early 1930s, Alexander Luria (1976) hypothesized that illiterates "would be unable to group objects – or even to pick out their abstract features – according to abstract semantic categories" and would "replace dominant abstract meanings with situations involving concrete practical experience" (p. 18). Luria reported that these predictions were confirmed: illiterates preferred situational thinking. For instance, they did not group objects into more abstract categories (e.g., tools, colors) and showed a strong focus on real world functions and everyday practical activities in their responses, e.g., referring to a geometrical circle as a *plate*, *sieve,* or *watch* (p. 27). Illiterates struggled to disregard specific features of an object and could not easily isolate commonalities within generic categories.

Indeed, recent research suggests that literacy and/or schooling may affect semantic knowledge and processing, at least quantitatively (Araújo et al., 2023; Denervaud et al., 2021). Schooled literate adults show more semantic fluency (more items produced) than unschooled illiterate even of ecologically relevant categories like domestic utensils (Kolinsky et al., 2014; Kosmidis et al., 2004; Reis & Castro-Caldas, 1997). They also outperform illiterates in tasks that require the identification of semantic similarities between words (Kolinsky et al., 2014; Ostrosky et al., 1998), being more likely to name *canary-parrot-swallow* as *birds* rather than using a more generic name like *animals*. It is, however, unclear whether this result is due to a lack of knowledge of the near superordinate name or concept (bird) or to difficulties in quick access to that knowledge by illiterates.

Learning to read is likely to enhance semantic memory, which could happen via vocabulary expansion because semantic knowledge is highly permeable to enrichment experiences (Denervaud et al., 2021; Vales et al., 2020). Reading is a gateway to learn new words and concepts, especially those that rarely or never occur in typical everyday oral interactions. Indeed, it has been found that children's picture books contain more words and more unique words – that is, have greater lexical density and diversity – than a matched sample of everyday conversations (Montag et al., 2015; Nation et al., 2022). What is still under debate, however, are the mechanisms by which literacy enhances lexical-semantic representations, and whether literacy can exert its influence independently of formal education and schooling.

One possibility is that literacy gives individuals "a better chance of adding new information (about spelling, pronunciation or meaning) to an impoverished representation" (Perfetti & Hart, 2002, p.192), leading to *finer-grained* or *sharpened representations* (Huettig & Pickering, 2019; Perfetti, 2007; Perfetti & Hart, 2002; Smith et al., 2014; Ziegler & Goswami, 2005). We hypothesize that literacy serves as one (or perhaps the primary) driving force for immersing readers in a rich linguistic context that continuously expands and, critically, also refines lexical-semantic representations. Recent findings seem to support this interpretation.

Araújo et al. (2019, 2023) provided empirical evidence that literacy speeds up semantic access to concrete concepts (e.g., objects) and especially to more abstract semantic representations (e.g., colors). Specifically, in a serial *Rapid Automatized Naming* (*RAN)* task, illiterate but not literate adults from the same socioeconomic background and informal settlement in Delhi, India, exhibited a notable category difference: basic color patches yielded much slower naming responses compared to everyday objects, despite both categories requiring similar phonological processing and all items being highly familiar (Araújo et al., 2023). Note that previous research suggests that better color naming is not a consequence of enhanced color perception or discrimination (Bornstein, 1985a, 1985b; Pitchford & Mullen, 2003) or of more practice (Brown, 1915; Ligon, 1932; Protopapas et al., 2017). It is semantic processing that has been postulated to be more effortful for color naming than for object naming (Anyan & Quillian, 1971; Bornstein, 1985a; Braisby & Dockrell, 1999; Kowalski & Zimiles, 2006; Pitchford & Mullen, 2001; Protopapas et al., 2017; Roelofs, 2003), because the former involves conceptualizing a feature (color) as an abstract property that is detachable from an object representation (Siuda-Krzywicka et al., 2020). Unlike concrete objects, colors lack inherent functional significance. Colors may also possess "blurred" categorical boundaries, leading to greater meaning ambiguity (e.g., Kowalski & Zimiles, 2006; Pitchford & Mullen, 2001). Thus, color naming is an example of a task that requires considerable abstraction. Notably, in line with Luria's (1976) suggestion that illiterates struggle to disregard specific features of an object, Araújo et al. (2023) observed that illiterates had particular difficulties in naming color patches compared to real world objects. This suggests that the lexical-semantic representations of color in illiterates may be less fine-grained or less sharp than the lexical-semantic representations of concrete objects.

In short, the recent findings of Araújo et al. (2023) open up a novel research avenue, suggesting the interesting possibility that literacy experience not only serves as a source of knowledge but also sharpens lexical-semantic representations (conceptual features, lexical concepts, and lexical representations). However, before drawing such a strong conclusion, the present study scrutinized three alternative explanations left open by Araújo et al. (2023) and aimed to provide generalizable evidence by testing a different population in Portugal.

First, the Araújo et al. study in India compared unschooled illiterate to schooled literate adults only, thereby confounding the impact of literacy per se with that of formal education or *schooling* (i.e., a broader learning context through which many other cognitive and knowledge acquisitions occur; see e.g. Dehaene et al., 2015). Indeed, previous research suggests that literacy and schooling can have dissociable effects. In the visual domain, for example, literacy (regardless of schooling) enhances orientation discrimination during object recognition across visual categories – a kind of skill that learning to read strongly demands in order to distinguish between similar graphemes such as the mirror-reversed "b" and "d" (Fernandes et al., 2021; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011) – whereas it is schooling that seems to promote the development of a more context-independent (analytic) visual processing style (Kolinsky et al., 1987; Kolinsky et al., 1990; Ventura et al., 2008). More importantly, recent advances in network estimation methods from fluency data suggest that the schooling context (Denervaud et al., 2021) and years of education (Siew & Guru, 2023) can shape the structure of semantic networks. Thus, it is unclear whether Araujo et al.'s results stem primarily from literacy or from formal schooling/education.

Second, Araújo et al.'s interpretation hinged on the assumption that the strong category effect in RAN by illiterates as opposed to literates reflects the efficiency of access to and processing of individual color concepts. However, serial RAN depends on the close coordination of several abilities, beyond individual stimulus processing, including sequencing of multiple items, eye-voice coordination, oculomotor programming, executive control, attention, and verbal working memory (Gordon & Hoedemaker, 2016; Henry et al., 2018; Kuperman et al., 2016; Protopapas et al., 2018). This is relevant because reading trains and fine-tunes all of these functions (Huettig & Hulstijn, 2024), potentially making RAN especially demanding for illiterate adults. Therefore, it is essential to determine whether the observed literacy effect truly reflects an influence on lexical-semantic processing rather than the task demands associated with multi-item naming.

Third, in regards to the mechanism of literacy-related sharpening of lexical-semantic representations, it is an open empirical question whether the impressive category effect observed by Araújo et al. is merely a byproduct of reading-induced vocabulary expansion (see e.g., Nation et al., 2001; Poulsen & Elbro, 2013).

In the present study, we thus used two tasks, one involving RAN and another involving *discrete naming* (i.e., naming individual items) of colors and objects, testing three groups of neurotypical adults from the same socioeconomic, cultural, and residential background in Portugal: unschooled and completely illiterate adults, unschooled ex-illiterate (who did not attend school in childhood but learned to read in adulthood through alphabetization courses), and schooled literate individuals. Importantly, the critical comparison between the two groups lacking formal schooling – illiterate and ex-illiterate – allows testing a potential dissociation of the effects of literacy from those that might arise as a consequence of schooling. We also collected estimates of receptive vocabulary size to clarify whether it would be a significant factor driving the literacy effect.

We hypothesized that if literacy (beyond schooling) is a driving force behind the differential performance of literates vs. illiterates in the color and concrete object categories, we should replicate the results of Araújo et al. (2023): no difference between naming latencies between the color and object categories among literates, but slower color naming compared to object naming in illiterates. The key comparison is the one with the additional group of unschooled ex- illiterates, who learned to read in absence of schooling. If the crucial stimulus category effect is related to literacy, ex-illiterates would show the same pattern of results as literates, that is, both groups of *readers* (literates an ex-illiterates) would exhibit no difference in naming of color vs. object categories (in contrast to illiterates). If, on the other hand, the stimulus category effect is primarily related to schooling, then, unschooled ex-illiterates would show the same effect of stimulus category as illiterates, that is, a significant difference in color vs. object naming.

2. Method

2.1. Participants

Seventy-one[1] Portuguese native speakers from the same residential and cultural background, and with similar socioeconomic status, participated voluntarily in the two experiments, after giving informed consent. They were from three groups,[2] based on schooling and literacy skills (see Table 1), and were matched in age, $F(2, 66) = 1.34$, $p = .27$, and female/male proportion, $X^2(2) < 1$: 31 unschooled and totally illiterate; 19 unschooled ex-illiterate, 19 schooled literate (with, on average, 8 years of schooling; $SD = 3.1$). Ex-illiterates learned to read and write as adults in special alphabetization courses, with all completing the fourth level, which corresponds not only to mastery of Initial Literacy Skills (focused on letter recognition, word formation, and constructing short sentences) but also to Basic Education Skills in reading (e.g., interpreting simple texts), writing, and arithmetic operations.

Illiterate and ex-illiterate participants were recruited through non-governmental organizations (NGOs). To ensure that the groups were as closely matched as possible, these NGOs also assisted in recruiting the literate group (in some cases, from the same families as the illiterate participants). All participants underwent a semi-structured interview, and all (ex-)illiterates self-reported that their lack of school during childhood was solely due to cultural or socioeconomic factors, which required them to begin working at an early age. For example, within the Roma community, to which all participants belong, females often face greater barriers to accessing education than males, driven by complex cultural dynamics (for background on the Romani population in Portugal, see Supplementary Material). None of the participants had a known neurological disorder or showed signs of cognitive decline, as confirmed by the Mini-Mental State Examination (MMSE; Portuguese version: Guerreiro et al., 1994). This confirms that illiteracy in our sample was not attributable to cognitive impairments.

We must acknowledge that, although we have considerable confidence that all participants supported by the NGOs were within a similar wage range, no objective measures of socioeconomic status were collected in this study. Importantly, prior work with a direct proxy for

Table 1
Participants' characteristics (M ± SD).

	Illiterate ($n = 31$)	Ex-Illiterate ($n = 19$)	Literate ($n = 19$)
Mean age (yrs)	40.7 ± 9.8	45.7 ± 11.1	41.1 ± 13.6
Age range	22–72	29–68	20–72
Female: Male ratio	21:10	13:6	13:6
Letter naming (out of 23)	7.9 ± 6.4[a]	21.7 ± 1.2[b]	22.8 ± 0.5[b]
Reading fluency 3DM (accuracy in 30 s)			
Words	0.1 ± 0.3[a]	28.4 ± 2.3[b]	29.8 ± 0.5[c]
Pseudowords	0.0 ± 0.0[a]	12.9 ± 2.3[b]	14.6 ± 0.7[c]
MMSE scores	19.3 ± 2.3[a]	21.7 ± 1.2[b]	22.1 ± 1.2[b]
Vocabulary (PPVT–4; max. = 96)	64.3 ± 8.2[a]	80.5 ± 6.4[b]	86.7 ± 4.7[c]

Note: MMSE scores were revised by discarding items examining reading, writing, and arithmetic abilities. Statistical analyses were conducted using ANOVA with Bonferroni-corrected post-hoc comparisons. Within each row, means sharing the same superscript letters (a, b, c) are not reliably different at the 5 % significance level.

[1] An a-priori power analysis run with MorePower 6.0 (Campbell & Thompson, 2012; Kumle et al., 2021) estimated the sample size required to detect a significant Group x Stimulus category interaction with an effect size of $\eta_p^2 = 0.16$, based on Araújo et al. (2023), with a power of 0.80. The minimum necessary sample size was 48.

[2] There is some overlap with participants from a previous study (Araújo et al., 2019; overlap: illiterates, $N = 7$; ex-illiterates, $N = 14$; literates, $N = 1$), but testing occurred 2.5-years apart, with no overlap in tasks except for the screening tests of MMSE, letter knowledge, and reading. Three illiterates in the present study were able to recognize one high-frequency word. We confirmed that the same statistical pattern holds with and without these participants.

socioeconomic status (monthly income in Rupees; Araújo et al., 2023) showed that literacy effects on naming are *not* confounded by socioeconomic factors that facilitate schooling and literacy acquisition.

Table 1 shows that, as expected, the groups differed considerably in letter knowledge (lowercase single-letter naming; 23 letters of the Portuguese alphabet, excluding the letters k, w, and y) and on reading fluency for single words and pseudowords (reading fluency test, assessing the ability to correctly read 75 pseudowords and 75 high- and low-frequency words of increasing syllabic complexity, with 30 s. allotted per block; Pacheco et al., 2014). The groups also differed on MMSE scores and vocabulary (reduced format of the Peabody Picture Vocabulary Test, PPVT–4, including 96 test items; Dunn& Dunn, 2007). Note that the MMSE is sensitive to literacy/educational levels (Crum et al., 1993) and education is associated with IQ and with vocabulary expansion (Ceci, 1990; Neisser et al., 1996). Importantly, we ensured that the same statistical results were found with MMSE-matched subgroups (see Supplementary Material). It is thus unlikely that the present results are due to differences in cognitive status, other than those related to literacy.

This study was approved by the Deontological Committee, Faculty of Psychology, Universidade de Lisboa, Portugal, and followed the international guidelines and the Portuguese regulation for research in Psychology. All participants were paid for time compensation.

2.2. Material and procedure

Database and material are available at https://osf.io/gmskh/?view_only=f94139f2c67148d9a67f8fd390c0feec.

The two naming tasks were administered immediately after the screening phase (i.e., semi-structured interview, MMSE, letter knowledge, and reading measures) in a fixed order: discrete naming preceded RAN to ensure that performance on the discrete naming task (which was novel relative to Araújo et al., 2023) was not contaminated by potential priming effects from RAN (in case the order was reversed). Because the RAN task aimed at replicating the pattern of results of Araújo et al. (2023), we present it first just for the sake of coherence.

The participants performed both naming tasks (see Fig. 1). It is worth noting that, at the time of data collection, additional tasks were administered as part of a larger ongoing project on literacy effects. However, no intervening tasks took place between the discrete naming and RAN tasks, ensuring the absence of carryover effects. Screening and naming tasks lasted approximately 50 min.

Rapid Automatized Naming (RAN) task: The object and color RAN tasks were as in Araújo et al. (2023; for an overview, see Araújo et al., 2015). Participants were asked to name as fast as possible in a left-to-right order five common objects (i.e., chair, fish, ring, trousers, tree; Portuguese pronunciation in IPA: [kɐ.dˈɐj.ɾɐ], [pˈɐj.ʃɨ], [ɐ.nˈɛɫ], [kˈaɫ.sɐʃ], [aɾ.vu.ɾɨ], respectively) and five basic color patches(i.e., green, blue, black, yellow, red; [vˈeɾ.dɨ], [ɐ.zˈuɫ]), [pɾˈe.tu], [ɐ.mɐ.ɾˈɛ.lu], [vɨɾ.mˈɐ.ʎu]), that were repeated four times each and were quasi-randomly arranged in four individual lines presented one at a time but in positions analogous to the classic RAN (Denckla & Rudel, 1976; with the criterion that no consecutive items had names that shared initial phonemes); the tasks were experimenter-paced, and participants' spoken output was recorded in parallel. The object and color categories were matched (*t*-tests, all *ps* > 0.5) in orthographic and phonological length, neighborhood density (P-PAL database; Soares et al., 2018), and word-form frequency (SUBTELEX-PT database; Soares et al., 2015). Importantly, by ensuring very close control over stimulus characteristics we guaranteed that both RAN tasks were comparable on their phonological access demands.

For each stimulus category, we created two sets with 20 items each (same objects/colors but in a different arrangement), and the category order was counterbalanced. Stimulus presentation and data collection were controlled by *E*-Prime Software. Participants were first given a practice, with corrective feedback. The mean time necessary to name the items of the two sets was used as a measure of RAN speed for each stimulus category; adobe audition sound editing software was used to preprocess the sound waves and locate the beginning and the end of the voiced parts.

Discrete naming task: The same stimuli and software as those in the RAN task were used but, in the discrete naming task, each stimulus (281 × 197 pixels) was presented one at a time at the center of the screen for a maximum of 3 s or until response (whatever came first). Participants were asked to name the stimulus aloud as quickly and accurately as possible. Stimuli were presented by stimulus category, with the order counterbalanced across participants. Before the experimental trials, participants performed five practice trials with other items from each stimulus category. Voice detection equipment was used to register RTs between the onset of the stimulus and the response; participants' spoken output was also recorded.

3. Results and discussion

3.1. RAN task

Accuracy was close to ceiling in both groups (> 98 %) and so was not analyzed further. For the whole-trial naming response times (RTs), the extreme values (i.e., greater than 2.5 SD beyond the group and stimulus category means) were winsorized (Wilcox, 2005; less than 2 % of the data). RTs were logarithmically transformed to ensure no violation of normality's assumptions.

For the sake of comparison with Araújo et al. (2023), mixed ANOVAs are reported in the Supplementary Material. We report here the analyses with linear mixed-effect models (LMM), as these models allow between-subject and between-item variance to be estimated simultaneously, and thus, to separate the experimental manipulation under observation from spurious or random effects (see e.g., Baayen et al., 2008; Quené & van den Bergh, 2008). LMM are particularly useful for analyzing data from heterogeneous groups, such as those with different reading levels. We used the lmer function of the lme4 package in R (Version 4.3.1).

We analyzed Group and Stimulus category effects (fixed-effects) on the log RTs, with Vocabulary (PPVT–4) as a continuous predictor (centered around zero; Brauer & Curtin, 2018), and by-subjects random intercepts and slopes, and by-trial random intercepts,[3] given that this theoretically-adequate LMM did converge and was the best fit (Barr et al., 2013; Matuschek et al., 2017). Following the omnibus Type III ANOVA, we examined the pattern of results with emmeans (Lenth, 2020) and computed planned contrasts as considered by Schad et al. (2020), with Tukey adjustment to control for Type I error. *P*-values were estimated using Satterthwaite approximations. Parameter estimates from the LMM are shown in Table 2.

The main effect of group, $F(2, 63.0) = 3.63$, $p = .032$, and the Group x Stimulus category interaction, $F(2, 63.0) = 6.96$, $p = .002$, were significant. Vocabulary was not a significant predictor, $F < 1$, $p = .657$, and it did neither significantly modulate the Group x Stimulus category interaction (Vocabulary x Group x Category: $F(2,63.0) = 2.73$, $p = .073$; Vocabulary x Group: $F(2,63.0) = 1.98$, $p = .147$). As shown in Fig. 2a, the performance of readers - ex-illiterate and literate - was not significantly affected by stimulus category, regardless of schooling (planned contrasts, literates: $\beta = -0.23$, SE $= 0.10$, $t = -2.28$, $p = .219$; ex-illiterates: $\beta = 0.02$, SE $= 0.05$, $t = 0.31$, $p > .9$). In contrast,

[3] Although the LMM with a more complex random structure (i.e., including by-Trial random intercept and slope) converged, it was near singularity and correlations between random effect estimates were 1.00, suggesting the model was overparameterized. Therefore, we keep a simpler model by dropping by-trial slopes. This model has lower AIC (−376.38) and a likelihood-ratio test indicates that the simplification of the random effects structure did not affect the model's adjustment. Equation used: lmer(RTs_log ~1 + Vocabulary*Group*Category + (1+ Category|SubjID) + (1|Trial), data = X).

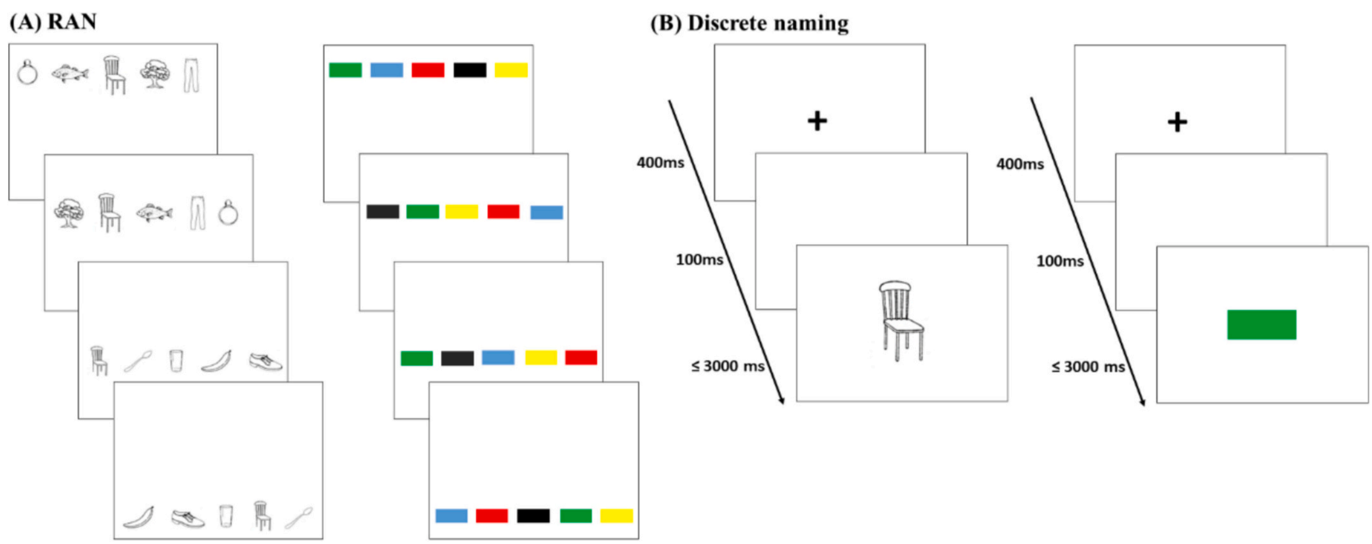

Fig. 1. (A) Example display of one trial of the object-RAN (left) and the color-RAN (right) tasks. (B) Sequence and duration of events on the discrete naming task with objects(left) and colors (right). In both tasks, objects were black-and-white line drawings, selected from the Snodgrass & Vanderwart set (Snodgrass & Vanderwart, 1980).

Table 2
LMEM fitted on log transform RTs in the RAN task.

LMEM: Experiment 1[a]					
Fixed effects					
	Estimate/ β	SE	t-statistic	df	p-value[b]
Intercept[c]	8.23	0.06	133.85	66.70	< 0.001
Vocabulary	−0.00	0.00	−0.99	63.00	0.328
Group Ex-Illiterates	−0.26	0.09	−2.99	63.00	< 0.005
Group Literates	−0.40	0.14	−2.82	63.00	0.006
Object-RAN	−0.16	0.05	−3.45	63.00	< 0.001
Vocabulary: Ex-Illiterates	0.01	0.01	1.27	63.00	0.209
Vocabulary: Literates	0.01	0.01	0.49	63.00	0.623
Vocabulary: Object-RAN	−0.00	0.00	−0.57	63.00	0.566
Ex-Illiterates: Object-RAN	0.15	0.07	2.19	63.00	0.032
Literates: object-RAN	0.39	0.11	3.53	63.00	<0.001
Vocabulary: Ex-Illiterates: Object-RAN	0.01	0.01	0.87	63.00	0.386
Vocabulary: Literates: Object-RAN	−0.02	0.01	−1.94	63.00	0.057
Random Effects					
			Variance	SD	
Participants (intercept)			0.038	0.194	
Participants (slope)			0.017	0.130	
Trial (intercept)			0.001	0.034	
Residual			0.029	0.171	
Model fit					
AIC (Aikake Information Criterion)			−376.4		
BIC (Bayesian Information Criterion)			−291.3		

Note: The reference level (treatment coding of contrasts) was the illiterate group and color-RAN.

illiterates were significantly slower on color than object RAN, $\beta = 0.16$, $SE = 0.05$, $t = 3.47$, $p = .012$. This interaction remained reliable when illiterates were specifically compared to ex-illiterates only, $F(1, 46.0) = 4.2$, $p = .047$, suggesting that the stimulus category effect was driven by literacy per se, rather than merely by schooling, which was not influenced by vocabulary (Vocabulary x Group x Stimulus category; $F(1, 46.0) = 0.7$, $p = .419$).

As shown in Fig. 2a, the literacy advantage was more pronounced for colors than for objects. Group comparisons confirmed that it was in color-RAN that illiterates were especially slower than ex-illiterates ($\beta = 0.26$, $SE = 0.09$, $t = 2.99$, $p = .043$) and literates ($\beta = 0.40$, $SE = 0.14$, $t = 2.82$, $p = .068$). The literacy advantage was less evident for object-RAN, with no significant difference observed between illiterate vs. ex-illiterates ($\beta = 0.11$, $SE = 0.08$, $t = 1.49$, $p = .673$) and vs. literates ($\beta = 0.01$, $SE = 0.13$, $t = 0.12$, $p > .9$). The two groups of readers did not differ from each other for any stimulus category (both $ps > 0.9$).

The interpretation that literacy has a direct association with rapid naming is further supported by the significant correlation observed between letter knowledge and (pseudo)word-reading fluency of ex-illiterate and literate adults and their performance on RAN tasks (for color naming: range $0.28 \leq r\,(36) \leq 0.40$; for object naming: range $0.37 \leq r\,(36) \leq 0.42$; unilateral test): the better their letter knowledge and reading fluency, the faster their RAN performance. This correlation cannot be due to an overall difference in speed between these two groups, as they did not significantly differ on RAN. In contrast, age, vocabulary, and MMSE scores were not reliable associated with RAN performance (see Supplementary Material for the full correlation matrix).

We thus replicated Araújo et al.'s (2023) findings in a different population from a different country, linguistic background, and ethnicity (here, European-Portuguese speakers from the Roma community in Portugal) and in a new, highly controlled setting, thus arguing for the generality of this stimulus category effect. Indeed, by including a group of unschooled ex-illiterate, we further demonstrated that literacy per se is a primary factor enhancing faster RAN of (depicted) lexical-semantic concepts, especially of those from more abstract categories, such as color. We do not contest that schooling might also play a broader role in lexical-semantic processing, given the overall performance gradient observed across the three groups (see Fig. 2). Nonetheless, the results from this task show that the differential influence of literacy on abstract versus concrete categories (being larger on colors than objects) cannot be attributed to vocabulary size nor it can be explained solely by schooling.

Note, however, that these results could reflect cumulative effects of lexical factors due to the sequential nature of RAN. Previous work has shown that RAN performance on any given item is strongly influenced by adjacent items (e.g., Compton, 2003; Easson et al., 2020). Additionally, RAN involves coordinating rapid serial eye movements and speech planning processes, executive attentional mechanisms, and verbal working memory (Amtmann et al., 2007; Gordon & Hoedemaker, 2016; Kuperman et al., 2016; Protopapas et al., 2018), and hence,

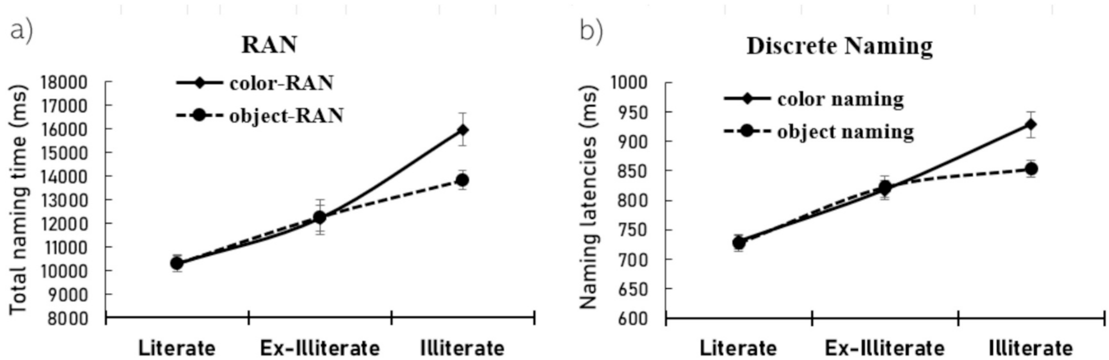

Fig. 2. a) Naming speed performance in object and color (dashed and full lines, respectively) RAN and b) discrete naming as a function of group. Naming times (in ms) after back-transforming from the log scale (means +/− SE).

imposes a greater cognitive challenge for illiterate people (e.g., Bramão et al., 2007; Demoulin & Kolinsky, 2016; Smalle et al., 2019). This cognitive orchestration may also specifically affect the efficiency of lexical-semantic processes (Shao et al., 2012). We thus examined if the differential role of literacy on stimulus category is RAN-specific or whether it generalizes to discrete naming.

3.2. Discrete naming task

Participants were highly accurate (> 98 % in all groups). RTs for correct responses were trimmed (2.5 SD above each participant's grand mean; 2.8 % of data excluded) and were log-transformed. The same model structure and equation used for the RAN task were adopted here to analyze log-transformed RTs for correct-response trials. Parameter estimates from the LMM are presented in Table 3.

Table 3
LMEM fitted on log transform RTs in the discrete naming task.

LMEM: Experiment 1[a]					
Fixed effects					
	Estimate/ β	SE	*t*-statistic	df	*p*-value [b]
Intercept [c]	6.83	0.03	203.69	66.12	< 0.001
Vocabulary	−0.00	0.00	−0.18	63.15	0.856
Group Ex-Illiterates	−0.14	0.05	−3.07	62.60	< 0.005
Group Literates	−0.17	0.08	−2.21	62.34	0.031
Object-naming	−0.08	0.02	−3.94	60.24	< 0.001
Vocabulary: Ex-Illiterates	0.00	0.00	0.96	62.86	0.339
Vocabulary: Literates	−0.01	0.01	−0.91	62.39	0.366
Vocabulary: Object-naming	−0.00	0.00	−0.03	61.74	0.980
Ex-Illiterates: Object-naming	0.11	0.03	3.52	60.44	<0.001
Literates: object-naming	0.09	0.05	1.78	58.94	0.080
Vocabulary: Ex-Illiterates: Object-naming	−0.00	0.00	−0.99	61.36	0.327
Vocabulary: Literates: Object-naming	−0.00	0.00	−0.11	59.29	0.910
Random Effects					
			Variance	SD	
Participants (intercept)			0.011	0.104	
Participants (slope)			0.003	0.052	
Trial (intercept)			0.001	0.026	
Residual			0.021	0.144	
Model fit					
AIC (Aikake Information Criterion)			−2316.0		
BIC (Bayesian Information Criterion)			−2216.1		

Note: The reference level (treatment coding of contrasts) was the illiterate group and color-naming.

As illustrated in Fig. 2b, the pattern of results in the discrete naming task was strikingly similar to that observed in the RAN task. The fixed effect Omnibus test showed a significant Group x Stimulus category interaction, $F(2, 59.6) = 6.46$, $p = .003$ (main effect of group: $F(2, 62.6) = 3.34$, $p = .042$). Similar to the RAN task, discrete naming of colors posed a great challenge to illiterate participants, as depicted by slower RTs compared to naming every-day objects (Tukey-adjusted contrasts, $\beta = 0.08$, $SE = 0.02$, $t = 3.94$, $p = .003$). In contrast, both ex-illiterate and literate did not show such category effect (both $ps > 0.9$). The interaction Group x Stimulus category was also reliable when illiterates were compared to ex-illiterates only, $F(1, 43.6) = 10.6$, $p < .005$, suggesting that this stimulus category effect was driven primarily by literacy rather than by schooling. Tukey-adjusted contrasts showed that the difference between illiterates and ex-illiterates essentially resided in color naming ($p = .036$; for object naming, $p > .9$). Similarly, illiterate participants were numerically slower in naming compared to schooled literates, particularly in color naming, although this difference was statistically significant only in the conventional mixed ANOVA (both $ps < 0.001$; see Supplementary Material) and not in the LMM analysis ($p = .250$ and 0.790 for color and object naming, respectively).

Neither the main effect of vocabulary nor any interaction with group was significant ($Fs < 1$ and $ps > 0.3$, Vocabulary x Group, $F = 1.1$).

In short, the effect of literacy is particularly pronounced in naming colors relative to concrete objects matched in word familiarity and psycholinguistic properties even when the task is one of discrete naming. In other words, the influence of literacy is robust and task-independent (at least in naming). It cannot be explained by vocabulary size and the role of schooling is secondary.

3.3. Cross-task comparison

Illiterates, in contrast to readers regardless of schooling, exhibited a notable category effect that spans both discrete and serial naming task formats. To further assess whether this interaction between group and stimulus category was indeed not qualified by task format, we conducted a cross-task analysis. Task was therefore included as a fixed effect in our model, with standardized scores (z-scores) to ensure comparability across tasks.

In this analysis, the three-way interaction between group, stimulus category, and task was significant, $F(2, 3558.4) = 4.53$, $p = .011$). The decomposition of this interaction confirmed that a simple effect of stimulus category was found in illiterates (RAN: $\beta = 0.54$, $SE = 0.14$, $t = 3.99$, $p = .004$; discrete naming: $\beta = 0.43$, $SE = 0.11$, $t = 4.08$, $p = .003$), but not in literates or ex-illiterates (all $ps > 0.2$). The magnitude of the color-naming deficit in illiterates did not significantly differ between tasks ($p = .791$). Nonetheless, in the color RAN task illiterates performed significantly worse than both literates ($\beta = 1.35$, $SE = 0.41$, $t = 3.32$, $p = .042$) and ex-illiterates ($\beta = 0.87$, $SE = 0.25$, $t = 3.48$, $p = .025$), but in discrete naming task their performance was more comparable (illiterates vs. literates: $p = .517$; illiterates vs. ex-illiterates: $p = .068$). To put it differently, illiterates' performance was particularly impaired in the serial RAN format, probably due to RAN higher cognitive demands relative to discrete naming (see, e.g., Araújo et al., 2015).

4. General Discussion

Humans rely on a richly organized semantic network of concepts to support vital cognitive feats such as object recognition, language production, and, more broadly, understanding the world that surrounds us. A fundamental question in the study of human cognition, besides how semantic knowledge is represented in the mind and brain (Frisby et al., 2023; Yee et al., 2018), concerns the way semantic representations can be shaped by specific cultural experiences. In this study, we addressed this question through the lens of literacy experience. We tested the hypothesis that literacy plays a central role, not only as a driving-source of knowledge accumulation, but also in sharpening lexical-semantic representations.

The present findings provide the strongest evidence to date that literacy per se, regardless of schooling, leads to faster naming of (depicted) concepts, and especially of more abstract categories such as colors. While the performance of readers – whether schooled (literates) or unschooled (ex-illiterates) – was not significantly influenced by stimulus category, illiterate adults were much slower on color than object naming, despite the high familiarity of both categories and similar phonological demands. The effect of literacy was consistent across tasks: illiterate adults were markedly slower in naming colors than everyday objects in both continuous (RAN) and discrete naming tasks, albeit the effect of literacy was stronger in the former probably due to RAN's high cognitive demands. In neither task the two groups of readers displayed an effect of stimulus category.

Our findings thus rule out the possibility that schooling alone, rather than literacy, drives the literacy-related category effect, as first reported by Araújo et al. (2023) in a sample from India. We can also confidently reject the hypothesis that the literacy advantage was due to the serial, multi-item processing required by the RAN task (Gordon & Hoedemaker, 2016; Henry et al., 2018; Protopapas et al., 2013; Protopapas et al., 2018). In a task more suitable for isolating lexical-semantic encoding without the added demands of multiple-item naming – that is, discrete naming – the same pattern of results was observed. Therefore, it is unlikely that task demands unrelated to lexical semantic-processing (see Araújo & Faísca, 2019; Araújo et al., 2015, for an overview) are a key factor in driving the differential effects of literacy on object versus color naming.

Furthermore, the present study shows that the influence of literacy is not dependent on culture at macro level, as Portuguese illiterates showed the same pattern of results as illiterates in India (Araújo et al., 2023), and interestingly, even when compared to ex-illiterate adults who, in turn, did not attend school during childhood and learned to read in adulthood.

Moreover, our matched design strongly refutes the possibility that the illiterates' results were driven by extraneous factors such as cultural, residential, or socioeconomic disadvantages: the same factors that limited opportunities for schooling in the illiterate group were present for the ex-illiterates. Hence, our study supports the notion that it is literacy per se rather than schooling or task demands that enhances the efficiency of access to and sharpness of lexical-semantic representations, with larger consequences for abstract concepts. It is remarkable that even rudimentary literacy, as seen in unschooled ex-illiterates, was found to exert such influence.

We note, however, the numerical gradient observed in naming times across the three groups in both tasks (i.e., the overall performance of ex-illiterates falling between illiterate and literate groups), although it did not reach statistical significance, possibly due to our relatively small sample size. Further research could usefully investigate this trend, as a statistically robust confirmation would suggest that, while literacy itself may have a more specific impact on lexical-semantic processes, certain broader aspects – such as general response speed or the ability to interpret two-dimensional visual representations (e.g., Reis et al., 2001) – may be contingent upon formal schooling. It is clear that school-related activities (including literacy activities) train a variety of perceptual and cognitive skills (e.g., working memory) and effective cognitive strategies, which may have consequences for cognition that are somewhat independent of reading and writing (e.g., Ardila et al., 2010; Kolinsky et al., 1987; Kolinsky et al., 1990; Kosmidis et al., 2006; Kosmidis et al., 2011). Indeed, the importance of education and enrichment learning experiences in shaping semantic networks (e.g., finer-grained within-domain distinctions) has recently been acknowledged (Denervaud et al., 2021; Siew & Guru, 2023; Vales et al., 2020). Our study provides further evidence that literacy experience speeds up access to lexical-semantic representations, while at the same time not ruling out the possibility that other processes involved in naming and processing speed are further cultivated through formal schooling and education, contributing to additional performance differences. Moreover, as with any quasi-experimental design, we cannot entirely rule out the influence of extraneous variables – such as broader life experience, individual motivation, or social support – that may have contributed to group differences, despite all participants being from the same community and socioeconomic background. Future research adopting a longitudinal design, including literacy training studies with adults (cf. Hervais-Adelman et al., 2019), would provide the most convincing converging evidence on the specific modulatory role of literacy.

More important, the influence of literacy goes beyond the mere acquisition and expansion of knowledge. While our results were compatible with the idea that vocabulary growth is related to individuals' formal education and literacy, vocabulary size does not mediate the impact of literacy in color naming. We can thus conclude that the effect of literacy is not a mere byproduct of vocabulary expansion. It is evident that literate and illiterate populations differ in the amount of exposure to print, but this disparity has broader implications than just the number of words acquired. Written input is conceptually and lexically richer than speech (Hayes, 1988; Montag et al., 2015; Nation et al., 2022), which in turn is the primary source of linguistic input for illiterate individuals. Reading may afford opportunities to refine pre-existing lexical representations in several ways (Huettig & Pickering, 2019; Smith et al., 2014; Ziegler & Goswami, 2005), not just through the acquisition of orthographic and more fine-grained phonological representations but also more fine-grained semantic representations and how semantic knowledge is interconnected. This aligns with previous evidence that readers perform better than nonreaders in tasks requiring mandatory semantic processing (object naming, semantic fluency, superordinate naming, similarities; Araújo et al., 2019; Kolinsky et al., 2014; Kosmidis et al., 2004; Ostrosky et al., 1998), and are also more likely to rely on prediction during spoken language processing (Huettig & Pickering, 2019), suggesting stronger lexical-semantic relations between concepts. Luo et al. (2023) proposed the notion that semantic representations of visual objects are flexibly encoded (i.e., updated) in semantic space to accommodate coarse/fine-grained label use. Similar links may exist for written language experience, possibly leading to more efficient representations in the semantic networks of readers.

The current findings, along with Araújo et al. (2023), further support the conclusion that literacy carries major weight for more abstract (object-independent) semantic categories. Indeed, abstract semantic representations are often more difficult for young children to learn (e.g., Bornstein, 1985a; Bornstein, 1985b; Pitchford & Mullen, 2001). Prior studies also suggest that literate versus illiterate performance differences are attenuated for items that are (presumably) less semantically mediated, such as numbers (Deloche et al., 1999), supporting the idea that the observed illiteracy-related naming cost is item-specific and linked to stimulus characteristics that increase the difficulty of lexical-semantic access.

One final aspect of our study design deserves further discussion. Color items were from a single homogenous semantic category, while objects were presented in a semantically heterogenous context, with exemplars from various categories (e.g., furniture, animal, clothing). Computational modeling (Oppenheim et al., 2010) and human data (Belke, 2013; Damian et al., 2001; Howard et al., 2006; Riley et al., 2015) from serial object-naming paradigms showed that semantically related items result in cumulative slowing of word retrieval compared to objects from different categories. This semantic interference is attributed either to competitive lexical selection (Howard et al., 2006) or competitive learning (Damian & Als, 2005; Oppenheim et al., 2010), where strengthening semantic-to-lexical connections of a target involves weakening the connections of co-activated non-target competitors, making them less accessible on a later trial. Thus, one possibility would be that the category effect found in illiterate adults here and in Araujo et al. (2023) would be due to less efficient executive control, which would explain such category effect due to semantic interference. However, such interpretation seems unlikely given that semantic interference is cumulative and linear (Howard et al., 2006), and typically absent on the initial presentation of each item (Belke & Stielow, 2013; Damian & Als, 2005 - Exp.4 A; Riley et al., 2015). In contrast, illiterates, relative to literate, were slower in naming since the very first encounter with colors (Araújo et al., 2023). Future studies may help to further delineate a potential influence of context on color and object naming in (il) literates.

To conclude, the current findings add to a growing body of literature providing strong evidence that literacy experience enhances cognitive skills beyond the realm of print (for an overview, see Dehaene et al., 2015; Huettig & Hulstijn, 2024; Kolinsky, 2015). Learning to read is associated with an enhanced ability to retrieve the names of everyday objects and, particularly, of semantically abstract entities such as color patches, irrespective of the task format. The cause of this influence is not simply a straightforward consequence of vocabulary expansion; rather, it is the experience of literacy that promotes further refinement towards more sophisticated lexical-semantic representations and processing.

CRediT authorship contribution statement

Susana Araújo: Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tânia Fernandes:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Margarida Cipriano:** Methodology, Investigation, Data curation. **Laura Mealha:** Investigation, Data curation. **Catarina Silva-Nunes:** Investigation, Data curation. **Falk Huettig:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Acknowledgements

We are thankful to the Comunitary Center of Ameixoeira and to Cáritas Diocesana de Beja and to AMUCIP for their help in participants' recruitment and testing facilities. This work was supported by FCT (ref. PTDC/PSI-GER/3281/2020) and the CICPSI R&D Unit funding UIDB/04527/2020 and UIDP/04527/2020. SA is supported by the FCT CEEC program (ref. 2021.03462.CEECIND).

Appendix A. Supplementary data

Material and data are publicly available at https://osf.io/gmskh/?view_only=f94139f2c67148d9a67f8fd390c0feec. Supplementary data to this article can be found online at [https://doi.org/10.1016/j.cognition.2025.106172].

Data availability

I have shared the link to my data/code/material at the main manuscript, which will be publicaly available

References

Amtmann, D., Abbott, R. D., & Berninger, V. W. (2007). Mixture growth models of RAN and RAS row by row: Insight into the reading system at work over time. *Reading and Writing, 20*, 785–813. https://doi.org/10.1007/s11145-006-9041-y

Anyan, W. R., & Quillian, W. W. (1971). The naming of primary colors by children. *Child Development, 42*, 1629–1632.

Araújo, S., & Faísca, L. (2019). A meta-analytic review of naming-speed deficits in developmental dyslexia. *Scientific Studies of Reading, 23*(5), 349–368. https://doi.org/10.1080/10888438.2019.1572758

Araújo, S., Fernandes, T., & Huettig, F. (2019). Learning to read facilitates the retrieval of phonological representations in rapid automatized naming: Evidence from unschooled illiterate, ex-illiterate, and schooled literate adults. *Developmental Science, e12783*. https://doi.org/10.1111/desc.12783

Araújo, S., Narang, V., Misra, D., Lohagun, N., Khan, O., Singh, A., … Huettig, F. (2023). A literacy-related color-specific deficit in rapid automatized naming: Evidence from neurotypical completely illiterate and literate adults. *Journal of Experimental Psychology: General, 152*(8), 2403–2409. https://doi.org/10.1037/xge0001376

Araújo, S., Reis, A., Petersson, K. M., & Faísca, L. (2015). Rapid automatized naming and reading performance: A meta-analysis. *Journal of Educational Psychology, 107*, 868–883. https://doi.org/10.1037/edu0000006

Ardila, A., Bertolucci, P. H., Braga, L. W., Castro-Caldas, A., Judd, T., Kosmidis, M. H., … Rosselli, M. (2010). Illiteracy: The neuropsychology of cognition without Reading. *Archives of Clinical Neuropsychology, 25*, 689–712. https://doi.org/10.1093/arclin/acq079

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modelling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*, 390–412.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255–278.

Belke, E. (2013). Long-lasting inhibitory semantic context effects on object naming are necessarily conceptually mediated: Implications for models of lexicalsemantic encoding. *Journal of Memory and Language, 69*, 228–256. https://doi.org/10.1016/j.jml.2013.05.008

Belke, E., & Stielow, A. (2013). Cumulative and non-cumulative semantic interference in object naming: Evidence from blocked and continuous manipulations of semantic context. *The Quarterly Journal of Experimental Psychology, 66*, 2135–2160. https://doi.org/10.1080/17470218.2013.775318

Berns, G. S., Blaine, K., Prietula, M. J., & Pye, B. E. (2013). Short- and long term effects of a novel on connectivity in the brain. *Brain Connectivity, 3*, 590–600. https://doi.org/10.1089/brain.2013.0166

Bornstein, M. H. (1985a). Colour-name versus shape-name learning in young children. *Journal of Child Language, 12*, 387–393.

Bornstein, M. H. (1985b). On the development of color naming in young children: Data and theory. *Brain and Language, 26*, 72–93.

Braisby, N., & Dockrell, J. (1999). Why is colour naming difficult? *Journal of Child Language, 26*, 23–47.

Bramão, I., Mendonça, A., Faísca, L., Ingvar, M., Peterson, K. M., & Reis, A. (2007). The impact of reading and writing skills on a visuo-motor integration task: A comparison between illiterate and literate subjects. *Journal of International Neuropsychological Society, 13*(2), 359–364.

Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables that vary within-subjects and/or within-items. *Psychological Methods, 23*(3), 389–411. https://doi.org/10.1037/met0000159

Brown, W. (1915). Practice in associating color names with colors. *Psychological Review, 22*(1), 45–55. https://doi.org/10.1037/h0073322

Campbell, J. I. D., & Thompson, V. A. (2012). MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behavior Research Methods, 44*(4), 1255–1265. https://doi.org/10.3758/s13428-012-0186-0

Carreiras, M., Seghier, M. L., Baquero, S., Estévez, A., Lozano, A., Devlin, J. T., & Price, C. J. (2009). An anatomical signature for literacy. *Nature, 461*, 983–986.

Ceci, S. J. (1990). How much does schooling influence general intelligence and its cognitive components? A reassessment of the evidence. *Developmental Psychology, 27*(5), 703–722.

Compton, D. L. (2003). The influence of item composition on RAN letter performance in first-grade children. *Journal of Special Education, 37*, 81–94. https://doi.org/10.1177/00224669030370020301

Crum, R. M., Anthony, J. C., Bassett, S. S., & Folstein, M. F. (1993). Population-based norms for the mini-mental-state-examination by age and educational-level. *Journal of the American Medical Association, 269*, 2386–2391.

Damian, M. F., & Als, L. C. (2005). Long-lasting semantic context effects in the spoken production of object names. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(6), 1372–1384. https://doi.org/10.1037/0278-7393.31.6.1372

Damian, M. F., Vigliocco, G., & Levelt, W. J. (2001). Effects of semantic context in the naming of pictures and words. *Cognition, 81*, B77–B86. https://doi.org/10.1016/s0010-0277(01)00135-4

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: Behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience, 16*, 234–244.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Filho, G. N., Jobert, A., … Cohen, L. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*, 1359–1364.
Dehaene-Lambertz, G., Monzalvo, K., & Dehaene, S. (2018). The emergence of the visual word form: Longitudinal evolution of category-specific ventral visual areas during reading acquisition. *PLoS Biology, 16*(3), Article e2004103.
Deloche, G., Souza, L., Braga, L. W., & Dellatolas, G. (1999). A calculation and number processing battery for clinical apllication in illiterates and semi-literates. *Cortex*, 503–521.
Demoulin, C., & Kolinsky, R. (2015). Does learning to read shape verbal working memory? *Psychological Bulletin and Review*. https://doi.org/10.3758/s13423-015-0956-7
Demoulin, C., & Kolinsky, R. (2016). Does learning to read shape verbal working memory? *Psychonomic Bulletin & Review, 23*, 703–722. https://doi.org/10.3758/s13423-015-0956-7
Denckla, M. B., & Rudel, R. G. (1976). Rapid "automatized" naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia, 14*, 471–479. https://doi.org/10.1016/0028-3932(76)90075-0
Denervaud, S., Christensen, A. P., Kenett, Y. N., & Beaty, R. E. (2021). Education shapes the structure of semantic memory and impacts creative thinking. *npj Science of Learning, 6*, 35. https://doi.org/10.1038/s41539-021-00113-8
Easson, K., Al Dahhan, N. Z., Brien, D. C., Kirby, J. R., & Munoz, D. P. (2020). Developmental trends of visual processing of letters and objects using naming speed tasks. *Frontiers in Human Neuroscience, 14*, Article 562712. https://doi.org/10.3389/fnhum.2020.562712
Fernandes, T., Arunkumar, M., & Huettig, F. (2021). The role of the written script in shaping mirror-image discrimination: Evidence from illiterate, Tamil literate, and Tamil-Latin-alphabet bi-literate adults. *Cognition, 206*, Article 104493.
Fernandes, T., & Kolinsky, R. (2013). From hand to eye: The role of literacy, familiarity, graspability, and vision-for-action on enantiomorphy. *Acta Psychologica, 142*, 51–61. https://doi.org/10.1016/j.actpsy.2012.11.008
Fernandino, L., Tong, J. Q., Conant, L. L., Humphries, C. J., & Binder, J. R. (2022). Decoding the information structure underlying the neural representation of concepts. *Proc Natl Acad Sci USA, 119*(6), Article e2108091119. https://doi.org/10.1073/pnas.2108091119
Frisby, S. L., Halai, A. D., Cox, C. R., Ralph, M. A. L., & Rogers, T. T. (2023). Decoding semantic representations in mind and brain. *Trends in Cognitive Sciences, 27*(3), 258–281. https://doi.org/10.1016/j.tics.2022.12.006
Gordon, P. C., & Hoedemaker, R. S. (2016). Effective scheduling of looking and talking during rapid automatized naming. *Journal of Experimental Psychology: Human Perception and Performance, 42*(5), 742–760. https://doi.org/10.1037/xhp0000171
Guerreiro, M., Silva, A. P., Botelho, M., Leitão, O., Castro-Caldas, A., & Garcia, C. (1994). Adaptação Portuguesa da tradução do Mini mental state examination (MMSE) [adaptation to the Portuguese population of the translation of the Mini mental state examination (MMSE)]. *Revista Portuguesa de Neurologia, 1*, 9–10.
Hayes, D. P. (1988). Speaking and writing: Distinct patterns of word choice. *Journal of Memory and Language, 21*, 572–585. https://doi.org/10.1016/0749-596X(88)90027-7
Henry, R., Van Dyke, J. A., & Kuperman, V. (2018). Oculomotor planning in RAN and reading: A strong test of the visual scanning hypothesis. *Reading and Writing: An Interdisciplinary Journal, 31*(7), 1619–1643. https://doi.org/10.1007/s11145-018-9856-3
Hervais-Adelman, A., Kumar, U., Mishra, R. K., Tripathi, V. N., Guleria, A., Singh, J. P., … Huettig, F. (2019). Learning to read recycles visual cortical networks without destruction. *Science Advances, 5*(9), eaax0262. https://doi.org/10.1126/sciadv.aax0262
Howard, D., Nickels, L., Coltheart, M., & Cole-Virtue, J. (2006). Cumulative semantic inhibition in picture naming: Experimental and computational studies. *Cognition, 100*, 464–482. https://doi.org/10.1016/j.cognition.2005.02.006
Huettig, F., & Hulstijn, J. (2024). The enhanced literate mind hypothesis. *Topics in Cognitive Science*. https://doi.org/10.1111/tops.12731
Huettig, F., & Pickering, M. (2019). Literacy advantages beyond reading: Prediction of spoken language. *Trends in Cognitive Sciences, 23*(6), 464–475. https://doi.org/10.1016/j.tics.2019.03.008
Kolinsky, R. (2015). How learning to read influences language and cognition. In A. Pollatsek, & R. Treiman (Eds.), *The Oxford handbook of Reading* (pp. 377–393). Oxford University Press.
Kolinsky, R., & Fernandes, T. (2014). A cultural side effect: Learning to read interferes with identity processing of familiar objects. *Frontiers in Psychology, 5(Research*. https://doi.org/10.3389/fpsyg.2014.01224. Topic: The impact of learning to read on visual processing), 1224.
Kolinsky, R., Monteiro-Plantin, R. S., Mengarda, E. J., Grimm-Cabral, L., Scliar-Cabral, L., & Morais, J. (2014). How formal education and literacy impact on the content and structure of semantic categories. *Trends in Neuroscience and Education, 3*(3–4), 106–121. https://doi.org/10.1016/j.tine.2014.08.001
Kolinsky, R., Morais, J., & Brito-Mendes, C. (1990). Embeddedness effects on part verification in children and unschooled adults. *Psychologica Belgica, 30*(1–2), 49–64.
Kolinsky, R., Morais, J., Content, A., & Cary, L. (1987). Finding parts within figures: A developmental study. *Perception, 16*(3), 399–407.
Kolinsky, R., Verhaeghe, A., Fernandes, T., Mengarda, E. J., Grimm-Cabral, L., & Morais, J. (2011). Enantiomorphy through the looking glass: Literacy effects on mirror-image discrimination. *Journal of Experimental Psychology. General, 140*, 210–238. https://doi.org/10.1037/a0022168
Kosmidis, M. H., Kyrana, T., & Folia, V. (2006). Lexical processing in illiteracy: Effect of literacy or education? *Cortex, 42*, 1021–1027. https://doi.org/10.1016/S0010-9452(08)70208-9
Kosmidis, M. H., Tsapkini, K., Folia, V., Vlahou, C. H., & Kiosseoglou, G. (2004). Semantic and phonological processing in illiteracy. *Journal of the International Neuropsychological Society, 10*(6), 818–827. https://doi.org/10.1017/s1355617704106036
Kosmidis, M. H., Zafiri, M., & Politimou, N. (2011). Literacy versus formal schooling: Influence on working memory. *Archives of Clinical Neuropsycholy, 26*(7), 575–582. https://doi.org/10.1093/arclin/acr063
Kowalski, K., & Zimiles, H. (2006). The relation between children's conceptual functioning with color and color term acquisition. *Journal of Experimental Child Psychology, 94*(4), 301–321. https://doi.org/10.1016/j.jecp.2005.12.001
Kumle, L., Võ, M. L.-H., & Draschkow, D. (2021). Estimating power in (generalized) linear mixed models: An open introduction and tutorial in R. *Behavior Research Methods, 53*, 2528–2543. https://doi.org/10.3758/s13428-021-01546-0
Kuperman, V., Van Dyke, J. A., & Henry, R. (2016). Eye-movement control in RAN and reading. *Scientific Studies of Reading, 20*(2), 173–188.
Lenth, R. (2020). Emmeans: Estimated marginal means, aka least-squares means. *R package version, 1*(4), 7. https://CRAN.R-project.org/package=emmeans.
Ligon, E. M. A. (1932). Genetic study of color naming and word reading. *American Journal of Psychology, 44*, 103–121.
Luo, X., Sexton, N. J., & Love, B. C. (2023). A deep learning account of how language affects thought. *Language, Cognition and Neuroscience, 38*(4), 499–508. https://doi.org/10.1080/23273798.2021.2001023
Luria, A. R. (1976). In M. Cole (Ed.), *Cognitive development: Its cultural and social foundations*. Harvard University Press.
Matuschek, H., Kliegl, R., Vasishth, S., Baayen, R. H., & Bates, D. (2017). Balancing type I error and power in linear mixed models. *Journal of Memory and Language, 94*, 305–315. https://doi.org/10.1016/j.jml.2017.01.001
Montag, J. L., Jones, M. N., & Smith, L. B. (2015). The words children hear: Picture books and the statistics for language learning. *Psychological Science, 26*(9), 1489–1496. https://doi.org/10.1177/0956797615594361
Nation, K., Dawson, N. J., & Hsiao, Y. (2022). Book language and its implications for children's language, literacy, and development. *Current Directions in Psychological Science, 31*(4), 375–380. https://doi.org/10.1177/09637214221103264
Nation, K., Marshall, C. M., & Snowling, M. (2001). Phonological and semantic contributions to children's picture naming skill: Evidence from children with developmental reading disorders. *Language & Cognitive Processes, 16*(2/3), 241–259.
Neisser, U., Boodoo, G., Bouchard, T. J., Jr., Boykin, A. W., Brody, N., Ceci, S. J., & Urbina, S. (1996). Intelligence: Knowns and unknowns. *American Psychologist, 51*(2), 77–101. https://doi.org/10.1037/0003-066X.51.2.77
Olivers, C. N. L., Huettig, F., Singh, J. P., & Mishra, R. K. (2014). The influence of literacy on visual search. *Visual Cognition, 22*(1), 74–101.
Oppenheim, G. M., Dell, G. S., & Schwartz, M. F. (2010). The dark side of incremental learning: A model of cumulative semantic interference during lexical access in speech production. *Cognition, 114*, 227–252. https://doi.org/10.1016/j.cognition.2009.09.007
Ostrosky, F., Ardila, A., Rosselli, M., López-Arango, G., & Uriel-Mendoza, V. (1998). Neuropsychological test performance in illiterates. *Archives of Clinical Neuropsychology, 13*(7), 645–660. https://doi.org/10.1093/arclin/13.7.645
Pacheco, A., Reis, A., Araújo, S., Inácio, F., Petersson, K. M., & Faísca, L. (2014). Dyslexia heterogeneity: Cognitive profiling of Portuguese children with dyslexia. *Reading and Writing: An Interdisciplinary Journal, 27*, 1529–1545.
Perfetti, C. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading, 11*(4), 357–383.
Perfetti, C., & Hart, L. (2002). The lexical quality hypothesis. In L. Verhoeven, C. Elbro, & P. Reitsma (Eds.), *Vol. 11. Precursors of functional literacy* (pp. 189–213). John Benjamins Publishing Company.
Pitchford, N. J., & Mullen, K. T. (2001). Conceptualization of perceptual attributes: A special case for color? *Journal of Experimental Child Psychology, 80*, 289–314.
Pitchford, N. J., & Mullen, K. T. (2003). The development of conceptual colour categories in pre-school children: Influence of perceptual categorization. *Visual Cognition, 10*, 51–77.
Poulsen, M., & Elbro, C. (2013). What's in a name depends on the type of name: The relationships between semantic and phonological access, Reading fluency, and Reading comprehension. *Scientific Studies of Reading, 17*(4), 303–314. https://doi.org/10.1080/10888438.2012.692743
Protopapas, A., Altani, A., & Georgiou, G. K. (2013). Development of serial processing in reading and rapid naming. *Journal of Experimental Child Psychology, 116*, 914–929.
Protopapas, A., Katopodi, K., Altani, A., & Georgiou, G. K. (2018). Word reading fluency as a serial naming task. *Scientific Studies of Reading, 22*(3), 248–263.
Protopapas, A., Markatou, A., Samaras, E., & Piokos, A. (2017). Shape and color naming are inherently asymmetrical: Evidence from practice-based interference. *Cognition, 158*, 122–133. https://doi.org/10.1016/j.cognition.2016.10.025
Quené, H., & van den Bergh, H. (2008). Examples of mixed effects modeling with crossed random effects and with binomial data. *Journal of Memory and Language, 59*, 413–425.
Reis, A., & Castro-Caldas, A. (1997). Illiteracy: A cause for biased cognitive development. *Journal of the International Neuropsychological Society, 3*(5), 444–450.
Reis, A., Petersson, K. M., Castro-Caldas, A., & Ingvar, M. (2001). Formal schooling influences two- but not three-dimensional naming skills. *Brain and Cognition, 47*, 397–411.
Riley, E., McMahon, K. L., & de Zubicaray, G. (2015). Long-lasting semantic interference effects in object naming are not necessarily conceptually mediated. *Frontiers in Psychology, 6*, 578. https://doi.org/10.3389/fpsyg.2015.00578
Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review, 110*(1), 88–125. https://doi.org/10.1037/0033-295X.110.1.88

Schad, D. J., Vasishth, S., Hohenstein, S., & Kliegl, R. (2020). How to capitalize on a priori contrasts in linear (mixed) models: A tutorial. *Journal of Memory and Language, 110*, Article 104038. https://doi.org/10.1016/j.jml.2019.104038

Shao, Z., Roelofs, A., & Meyer, A. S. (2012). Sources of individual differences in the speed of naming objects and actions: The contribution of executive control. *The Quarterly Journal of Experimental Psychology, 65*(10), 1927–1944. https://doi.org/10.1080/17470218.2012.670252

Siew, C. S. Q., & Guru, A. (2023). Investigating the network structure of domain-specifc knowledge using the semantic fuency task. *Memory & Cognition, 51*, 623–646. https://doi.org/10.3758/s13421-022-01314-1

Siuda-Krzywicka, K., Witzel, C., Taga, M., Delanoe, M., Cohen, L., & Bartolomeo, P. (2020). When colours split from objects: The disconnection of colour perception from colour language and colour knowledge. *Cognitive Neuropsychology, 37*(5–6), 325–339. https://doi.org/10.1080/02643294.2019.1642861

Skeide, M. A., Kumar, U., Mishra, R. K., Tripathi, V. N., Guleria, A., Singh, J. P., & Huettig, F. (2017). Learning to read alters cortico-subcortical cross-talk in the visual system of illiterates. *Science Advances, 3*, Article e1602612.

Smalle, E., Szmalec, A., Bogaerts, L., Page, M. P. A., Narang, V., Misra, D., & Huettig, F. (2019). Literacy improves short-term serial recall of spoken verbal but not visuospatial items - evidence from illiterate and literate adults. *Cognition, 185*, 144–150. https://doi.org/10.1016/j.cognition.2019.01.012

Smith, A. C., Monaghan, P., & Huettig, F. (2014). Literacy effects on language and vision: Emergent effects from an amodal shared resource (ASR) computational model. *Cognitive Psychology, 75*, 28–54. https://doi.org/10.1016/j.cogpsych.2014.07.002

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 6*, 174–215.

Soares, A. P., Iriarte, A., Almeida, J. J., Simões, A., Costa, A., Machado, J., & Perea, M. (2018). Procura-PALavras (P-PAL): A web-based interface for a new European Portuguese lexical database. *Behavior Research Methods, 50*(4), 1461–1481. https://doi.org/10.3758/s13428-018-1058-z

Soares, A. P., Machado, J., Costa, A., Iriarte, A., Simões, A., Almeida, J. J., & Perea, M. (2015). On the advantages of word frequency and contextual diversity measures extracted from subtitles: The case of Portuguese. *Quarterly Journal of Experimental Psychology, 68*(4), 680–696.

Stine-Morrow, E. A. L., McCall, G. S., Manavbasi, I., Ng, S., Llano, D. A., & Barbey, A. K. (2022). The effects of sustained literacy engagement on cognition and sentence processing among older adults. *Frontiers in Psychology, 13*, Article 923795. https://doi.org/10.3389/fpsyg.2022.923795

Vales, C., States, S. L., & Fisher, A. V. (2020). Experience-driven semantic differentiation: Effects of a naturalistic experience on within- and across-domain differentiation in children. *Child Development, 91*(3), 733–742. https://doi.org/10.1111/cdev.13369

Van Paridon, J., Ostarek, M., Arunkumar, M., & Huettig, F. (2021). Does neuronal recycling result in destructive competition? The influence of learning to read on the recognition of faces. *Psychological Science, 32*, 459–465. https://doi.org/10.1177/0956797620971652

Ventura, P., Pattamadilok, C., Fernandes, T., Klein, O., Morais, J., & Kolinsky, R. (2008). Schooling in western culture promotes context-free processing. *Journal of Experimental Child Psychology, 100*(2), 79–88. https://doi.org/10.1016/j.jecp.2008.02.001

Wilcox, R. R. (2005). *Introduction to robust estimation and hypothesis testing* (2nd ed.). Elsevier Academic Press.

Yee, E., Jones, M. N., & McRae, K. (2018). Semantic memory. In J. T. Wixted, & S. L. Thompson-Schill (Eds.), *Stevens' handbook of experimental psychology and neuroscience* (4th ed., pp. 319–356). Wiley. https://doi.org/10.1002/9781119170174.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*(1), 3–29. https://doi.org/10.1037/0033-2909.131.1.3