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How to cite

ARDANOUY, Estelle et al. Which skills underlie French-speaking children's lexical spelling acquisition in elementary school? Insight from a cross-sectional exploratory network study from Grade 1 to Grade 5. In: Journal of experimental child psychology, 2024, vol. 245, p. 105963. doi: 10.1016/j.jecp.2024.105963

This publication URL: https://archive-ouverte.unige.ch/unige:177500
Publication DOI: 10.1016/j.jecp.2024.105963

Journal of Experimental Child Psychology 245 (2024) 105963

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

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

Which skills underlie French-speaking children's lexical spelling acquisition in elementary school? Insight from a cross-sectional exploratory network study from Grade 1 to Grade 5

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ARTICLE INFO

Article history:
Received 18 August 2023
Revised 16 April 2024

Keywords:
Spelling
Children
Morphology
Phonology
Graphotactic regularities
Acquisition

ABSTRACT

Learning to spell in an inconsistent orthographic system is a true challenge for primary school children. Previous empirical studies have highlighted three main skills involved in this learning process: phonological skills, morphological skills, and children's sensitivity to graphotactic regularities. However, the literature shows contradictions in the exact nature of the contribution of each skill at different stages of the learning process. So, the aim of our study was to test the contribution of this set of skills in the acquisition of lexical spelling as a function of children's grade level. For this purpose, we assessed these dimensions in a cross-sectional sample of 1101 French-speaking children from Grade 1 to Grade 5. The analyses were conducted using data-driven exploratory network modeling. The results showed (a) a predominant role of phonological skills at the beginning of learning, which tends to decrease with advancing schooling; (b) an increasing contribution of morphological skills from Grade 1 to Grade 5 with a drop in Grade 4, which is the only contribution that continues to increase in Grade 5; and (c) a contribution of the sensitivity to graphotactic regularities that tends to be stable until Grade 4 before decreasing in Grade 5. Our findings show the importance of all three skills in a dynamic process in learning to spell. The implications of these results are

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https://doi.org/10.1016/j.jecp.2024.105963

discussed in light of the *integration of multiple patterns* model of learning to spell.

Introduction

Spelling is the written graphic representation of oral language (Fayol & Jaffré, 2014), and its mastery is an important predictor of secondary school choice and academic success (Savolainen et al., 2008). Adolescents with reading and spelling difficulties are less likely to enter post-secondary programs (Murray et al., 2000). Spelling proficiency is also a skill required for professional success and social integration in addition to obvious factors such as choice of school subjects and study success (Graham & Harris, 2005). Given the importance of spelling in our society, it is critical to understand how it develops over the years in children (Treiman, 2017). Alphabetic systems (such as English and French) are based on the mappings between graphemes and phonemes in reading and between phonemes and graphemes in spelling. The degree of consistency between graphemes and phonemes defines the transparency of a language, and it can be computed separately for reading and spelling. Hence, the more the number of graphemes is equal to the number of phonemes, the more this language will be considered as transparent. Some languages are shallow in reading and spelling (e.g., Spanish, Croatian), others are regular in reading but not in spelling (e.g., French, Farsi), and still others are opaque in both directions (e.g., English). Ziegler and colleagues (1996) estimated that the consistencies of French and English were about 20.9% and 27.7%, respectively, from phonemes to graphemes (i.e., in spelling) for monosyllabic words. So, French is more opaque in spelling than in reading, which could add to the difficulty to learn to spell.

Several studies have shown that spelling consistency has an impact on spelling acquisition; children who learn to spell in a language with a deep orthography make slower progress than those using a shallow orthography (Caravolas, 2004). Some authors have highlighted other skills involved in learning to spell such as morphological skills, graphotactic regularities, and specific learning skills, that is, rote memorization of word spelling difficulties (Fayol, 2009; Pacton et al., 2013, 2018; Treiman, 2017). However, very few studies, especially in French, have examined the development of these skills during the learning of spelling and their role during schooling. Therefore, this study assessed phonological, morphological, graphotactic, and other important language and cognitive skills (vocabulary and nonverbal reasoning) in a large cross-sectional sample of elementary school children from Grade 1 to Grade 5 in order to test the link between these factors and their contribution to lexical spelling across age.

Characteristics of French spelling

Several specificities of written French need to be taken into consideration to better appreciate its complexity, namely morphology, etymology, homophones, and historical remains (Gak, 1976). First, French is rich for its productivity in derivational morphology, with about 170 suffixes (compared with 50 in use in English), which offers greater possibilities of word composition (Duncan et al., 2009). This might explain why French-speaking children have an easier time generalizing the learning of derivational morphology than their English peers (Casalis et al., 2015). Rey-Debove (1984) estimated that about 80% of the words in the French dictionary *Robert méthodique* were morphologically complex. Moreover, the spelling of French has morphological markings that are not heard orally; for example, "petit" [small] has a final silent "-t" that is pronounced in words of the same family: "petite, petitesse" [small-FEM, smallness]. In the Silex database, the percentage of words ending with a silent letter is estimated at 28%, and this percentage increases to 56% for inflected words (Gingras & Sénéchal, 2017). Some of these silent letters come from the etymology of the language itself given that some words have etymological markings that recall their origin (Fayol & Jaffré, 2014). For example, the letter

h, which is silent in French, was kept in words where it was pronounced in Latin (“homme” /ɔm/ [man] from Latin “homo”). Another example is the word “sept” /sɛt/ [seven], which contains a silent letter /p/ that was present in the Latin word “septem.” Furthermore, some morphological markings allow for the differentiation of written homophones. For example, the homonym words “verre, vert, vers, ver” [glass, green, toward, worm] have entirely different meanings. Finally, historical markings are present in French. It is sometimes the case for the use of accents (Fayol & Jaffré, 2014). For example, the circumflex accent in some words has replaced the diacritic letter *s*, which has disappeared from Old French words (as the /s/ sound disappeared from its pronunciation) as an historical marking of its presence (“forest” became “forêt” [forest]).

Cognitive model of spelling

Spelling skill acquisition emerges through explicit and formal learning as well as through implicit knowledge. Alegria and Mousty (1996) adapted dual-route reading models to spelling. In this model, a first spelling route corresponds to an analytic procedure in which the heard word is segmented into phonemes and then transcoded into graphemes. Then, the graphemes are assembled to form the “word” entity. This route is based on the explicit learning of phoneme–grapheme correspondences. In French, however, spelling through phoneme–grapheme correspondence rules leads to the correct spelling of only 50% of words (Pacton & Afonso-Jaco, 2015). Therefore, a second procedure is needed, namely the orthographic route, in which there is direct access to the written representation of the word, which is retrieved from the orthographic lexicon. This direct route allows for the spelling of familiar words that have already been encountered and encoded, whether consistent or inconsistent. Several authors have adapted the model to include interaction between the two routes (Rapp et al., 2002; Tainturier, 2013); in this way, both are activated in parallel, but the weight of their respective contributions varies as a function of the degree of familiarity with the word to be spelled (known or unknown). An increasing number of words are hypothesized to be stored in the orthographic lexicon (Sprenger-Charolles et al., 2003), but existing studies do not allow us to say whether this memorization is the result of simple (implicit) exposure to the writing or an explicit type of learning by memorization (Martinet et al., 2004; Sprenger-Charolles et al., 2003). However, we know that children do not wait until they master all the phoneme–grapheme correspondences to build orthographic representations given that this process can already be observed after only 3 months of literacy learning, in Grade 1 (Martinet et al., 2004).

Nevertheless, several authors have shown that this dual-route model does not account for all the skills that have been identified in empirical studies on spelling learning such as morphological knowledge and sensitivity to graphotactic regularities (Deacon & Bryant, 2006; Kessler et al., 2013; Pacton et al., 2013, 2018). Treiman and colleagues (Treiman, 2017; Treiman & Kessler, 2014) proposed a theory of learning referred to as the integration of multiple patterns (IMP). When learning to spell a word, children use probabilistic and deterministic patterns. The more the patterns converge in the same direction, the easier it is for learners to memorize the spelling of a word. These patterns emerge with the overlapping of children’s phonological (context-conditioned links from sound to letter), morphological, and graphotactic skills. Learning to spell according to this hypothesis involves learning to master implicitly or explicitly these different patterns through reading and spelling (Conrad et al., 2019).

Factors contributing to spelling skills development

Phonological skills

Several studies have reported that spelling skill development draws from different underlying cognitive skills. In the state of the scientific literature, the most reliable predictor of spelling proficiency seems to be phonological awareness, especially in languages with a deep orthography like English (Caravolas, 2004; Furnes & Samuelsson, 2010) and French (Plaza & Cohen, 2003; Sanchez et al., 2012). The relationship between phonological awareness and spelling appears to be causal given that phonological awareness training improves the learning of written language (Suggate, 2010, 2016; Torgesen, 2000).

More specifically, in the dual-route model previously described (Alegria & Mousty, 1996), the analytical procedure—that is, the knowledge of phoneme–grapheme correspondences—rests on phonological skills. In early learning, this knowledge is essential and necessary to start the acquisition of spelling thanks to this generative process (Fayol, 2009; Sprenger-Charolles et al., 2003) in the same way that phonological decoding is crucial for learning to read (Share, 1995, 1999). Indeed, from a limited number of acquired graphophonological correspondences, the learner can decode a large number of words and consolidate the acquisition of these correspondences, a strategy that Share (1995, 1999) called "self-teaching" or "self-fed teaching." In addition to phonological recoding, the child can associate the oral form of the word with its written form and spelling features. The more the learner encounters the same words, the more the learner will retain their particularities (Cunningham, 2006; Cunningham et al., 2002). Therefore, this learning is largely implicit. However, reading words to learn their spelling is not sufficient (Chaves et al., 2012; Treiman, 1998), as demonstrated by two phenomena. The first is the double dissociation between reading and spelling that is observed in several languages with varying degrees of consistency (Moll & Landerl, 2009; Wimmer & Mayringer, 2002). These studies report the existence of several groups of children: good readers/good spellers, poor readers/poor spellers, good readers/poor spellers, but also poor readers/good spellers. This dissociation between reading and spelling, even though it applies to a small number of children, highlights the shortcoming of reading for the development of spelling and vice versa. The second phenomenon corresponds to the fact that average correlations between reading and spelling typically range from.60 to.80 (Bosman & van Orden, 1997; Ehri, 1997), which suggests that the two skills do not operate in exactly the same way. Consequently, the knowledge of phoneme–grapheme correspondences is necessary, but given the inconsistency of some languages (such as English and French), it is insufficient to learn to spell. In addition to phonological skills, other skills come into play, in particular morphological skills, graphotactic rules, and specific orthographic skills (Castles & Nation, 2006; Fayol, 2009; Treiman, 2017; Treiman & Kessler, 2014).

Morphological skills

Morphology concerns the study of complex word composition and, more specifically, the study of morphemes that correspond to the smallest units carrying meaning within the word (Nagy et al., 2014). Morphology encompasses two main areas: inflectional morphology, which is related to syntax (e.g., gender and number agreement), and derivational morphology, which was our focus here. Derivational morphology deals with word formation and, in this way, allows the creation of new words by adding a prefix or suffix to a root. Morphology also plays an important role in learning how to spell words (Pacton et al., 2018). Specifically in English-speaking children, Deacon and colleagues (2009) established the presence of a predictive contribution of morphological awareness[1] to spelling; the level of morphological awareness in Grade 2 explained a significant part of the variance of spelling in Grade 4. The same contribution was found in French (Casalis et al., 2011; Desrochers et al., 2018). Furthermore, a couple of other studies have indicated that French-speaking children are sensitive to morphological derivation processes in their language at an earlier age than age-matched English-speaking children in both the oral form (Duncan et al., 2009) and written form (Casalis et al., 2015).

Another argument that supports the contribution of morphology in learning to spell is that French-speaking children spell better inconsistent words that have a morphological explanation than those that do not (Pacton & Deacon, 2008). Thus, several studies have been conducted on the final silent letters of words; they show that children write the silent letter correctly more often in the morphological condition, that is, when children can use a word of the same morphological family (Pacton et al., 2018; Sénéchal et al., 2006). For instance, the word "bavard" [chatty] is more often correctly spelled because one can use the words "bavarder" [chat] and "bavardage" [chatting] to infer the silent letter, as compared with "foulard" [scarf], which has no morphological derivative. A study by Casalis and colleagues (2011) showed that children indeed spell the grapheme /ai/ better in the root of words that have morphological derivatives such as "lait" [milk] ("laiterie" [dairy], "laitier" [milkman]) than words without

[1] Morphological awareness is the ability to consciously analyze and manipulate the morphological structure of words into smaller meaningful units (Carlisle, 1995).

derivatives such as "falaise" [cliff]. Thus, it seems that learners use their morphological knowledge to write related words (Pacton & Deacon, 2008).

Although phonological and morphological skills are essential for accurate spelling, they are still not sufficient; orthographic processing skills are also required. These processes include both specific lexical representations and general sublexical representations, namely graphotactic regularities and rules (Berninger et al., 1994).

Graphotactic regularities

As children get exposed to print, they progressively and implicitly become sensitive to the statistical regularities and rules that govern their orthographic system in terms of the frequency of occurrence of letters and in terms of transitional probabilities between letters/graphemes within written words. The rules concern ways of writing a word that are always valid for a given language. For example, French words cannot end with the spelling "-je". The regularities concern more probable spellings than others; for example, the sound [ɛ̃] at the beginning of a word is more often spelled /in/ than /ain/. Children rapidly become able to decide whether a written word is admissible or not in the lexicon on the basis of its form even though they do not always know its meaning (Jaffré & Fayol, 1997). For example, between the two pseudowords "gupprane" and "guprrane", French-speaking children will choose the former as being a more French-like candidate than the latter because French does not allow the doubling of the second consonant in a consonant cluster (Pacton et al., 2013). From the first year of exposure to written language, graphotactic regularities affect children's orthographic productions in both English and French (Castles & Nation, 2006; Pacton et al., 2001). Another example is that beginning readers quickly develop a sensitivity to the oddity of double consonants in word-initial position in these languages (e.g., *nnetuque; Cassar & Treiman, 1997; Pacton et al., 2013). Graphotactic sensitivity can also be linked to conditional regularities: the presence or absence of a letter before a target grapheme. The "-ette" grapheme [ɛt] is more often used after a *v* or an *r* than after an *f* (as in *crevette* "shrimp"), and the "-eau" grapheme [o] is more often used after "-r" than after "-f" (as in *bureau* "desk") (Pacton et al., 2005). Finally, the detailed acquisition of the various graphotactic rules has been little studied, an issue that deserves further attention.

Specific orthographic skills

When a word does not conform to phonological regularities or to morphological rules, another option is to rely on specific orthographic knowledge (Pacton & Afonso-Jaco, 2015). Inconsistent forms that have no explanation must then be memorized by rote. For example, the reason why the phoneme /e/ is transcribed by the letters *on* in the French word "monsieur" /məsjø/ [mister] is historical and does not follow any rule in modern French. Similarly, in English, the selection of the correct transcription of the phoneme /i:/ among the 11 possible graphemes (i.e., *e, i, ee, ea, ae, ei, ie, ey, ay, eo*, and *oe*) often depends on word-specific information (Sprenger-Charolles & Béchennec, 2004). However, this rote memorization, according to the IMP theory, is constructive (Treiman & Kessler, 2014). These latter authors explained that the elaboration of orthographic representation would rely on the activation of phonological, morphological, or graphotactic patterns, which would help us to memorize the spelling of even very inconsistent words. These memorized forms constitute the orthographic lexicon, corresponding to the direct/orthographic route of the Alegria and Mousty (1996) model.

Developmental course of lexical spelling

Several studies have reported that the development of lexical spelling is nonlinear. For instance, a study by Martinet et al. (2004) reported that some lexical knowledge was already established in Grade 1, after only 3 months of formal literacy teaching, whereas the most frequent grapheme–phoneme correspondences had not yet been fully acquired. Moreover, Fayol and colleagues (2020) reported that the spelling of /i/ and /u/ endings changed with age. In Grade 2 children made simplifications (omission of the final letter *e*, as in the word "tortue" [turtle] written *tortu), whereas in Grade 3 they preferentially added a silent *e* (e.g., erroneous addition of a silent *e* at the end of "individu" [individual]; replacement of the final silent letter by an *e*, as for the word "tapis" [carpet] written *tapie). Finally, in

Grades 4 and 5 they made word endings more complex even when words had a transparent final letter (as in the word "fourmi" [ant] written *fourmit or *fourmis).

In addition, Bahr and colleagues (2012) profiled English-speaking children's spelling errors based on their grade from 1 to 9. The task they used was written text production, whereby students were asked to tell about their best (or worst) day at school. The authors proposed a classification of errors according to three main areas: (a) orthographic errors on the lexical spelling of words, (b) phonological errors, and (c) morphological errors—contractions (*weve/we've), homonyms (there/their), inflections (plural), and derivations (*practly/practically). The results indicated a decrease in orthographic errors when grade level increased, with errors remaining quite high in older participants (52% in Grade 1 and still 36% in Grade 9), as well as a decrease in phonological errors (26% of errors in Grade 1 vs. 12% in Grade 9), but also an increase in morphological errors (7% in Grade 1 vs. 22% in Grade 9) on all types of errors (contractions, homonyms, inflections, and derivations). Similar results were found in Joye and colleagues' (2022) study with French-speaking children tested from Grade 1 to Grade 5. Phonological and spelling errors were less important in French-speaking children (15% in Grade 1 and less than 1% in Grade 5 for phonological errors and 42% in Grade 1 and 21% in Grade 5 for spelling errors), and morphological errors outweighed the other types of errors (39% in Grade 1 and 74% in Grade 5). As the authors suggested, this pattern of results could be due to the complexity of French inflectional spelling. However, the results were different on a word dictation task, with orthographic and morphological errors reversing their trend (61% to 78% for orthographic errors and 16% to 8% for morphological errors from Grade 1 to Grade 5), showing a progressive mastery of derivational morphology in French-speaking children. These findings are consistent with other studies showing that phonological skills predict literacy in the early years of learning (e.g., Grade 1), whereas morphological skills predict literacy outcomes in Grade 2 and beyond (Ardanouy et al., under review; Casalis & Louis-Alexandre, 2000; Desrochers et al., 2018).

Aim of the study

As mentioned, several studies have focused on the spelling skills related to successful spelling, which include phonological skills, morphological skills, and graphotactic regularities (Casalis et al., 2011; Pacton & Deacon, 2008; Pacton et al., 2005; Sprenger-Charolles et al., 2003; Treiman, 2017). However, to our knowledge, no study has tested the relative contribution of each of these three skills as a function of children's grade level. In addition, although the importance of these skills for lexical spelling is well-recognized, we do not know how these skills relate to each other or how they relate to broader measures such as vocabulary level and nonverbal reasoning. Thus, the goal of the current study was to verify and assess the contribution of these three factors to lexical spelling in French-speaking children aged 6 to 11 years (Grade 1 to Grade 5 of primary school). Given the lack of an established model of spelling acquisition, we decided to use an exploratory network analysis method. The data-driven exploratory network modeling addressed two research goals. First, we examined the relation between the skills (i.e., phonology, morphology, and graphotactic) and lexical spelling, taking into account vocabulary level and nonverbal reasoning. Second, we established the weight of the three skills in relation to lexical spelling throughout the grades. Even though the subsequent analyses are entirely data-driven, the literature reviewed above allowed us to formulate some general hypotheses. We expected that all skills would not be mastered at the same pace and that they might not serve the same purposes. We anticipated the contribution of phonological skills to predominate in the early stages of learning to spell and to slowly decline until the end of Grade 5 (as in Sprenger-Charolles et al., 2003). As for morphological skills, they should emerge as an explanatory variable from Grade 1 until they become more important skills contributing to differentiate inter-individual lexical levels in Grade 5 (see Casalis & Louis-Alexandre, 2000; Desrochers et al., 2018; Joye et al., 2022). Finally, graphotactic regularities should emerge as an early predictor of spelling (Pacton et al., 2001; Treiman & Kessler, 2006) and should remain present throughout the primary grades (Pacton & Deacon, 2008; Pacton et al., 2005).

Method

Participants

We recruited 1151 participants from Grade 1 to Grade 5 in 14 French and Swiss public schools in Geneva area. The socioeconomic level of the participants was diverse, with 2 of the schools being part of the priority education network (REP[2]) where the socioeconomic level is low (280 children), 3 schools being located in advantaged areas (203 children), and the rest of the schools being located in economically average settings (668 children). The faculty ethics committee of the University of Geneva granted approval for the current research. All parents received detailed information on the study and signed the consent form. Children also gave oral consent to participate in the study. We ultimately included 1102 children in our study after excluding all children who had a diagnosis of a learning disability (n = 11), who did not learn French before 3 years of age (n = 4), or for whom data were incomplete (n = 34). Regarding the distribution of children, 341 participants were from Swiss schools and 760 participants were from French schools. We used a series of independent two-way t tests to verify that the results between the French and Swiss participants by grade level were not significantly different. We found no statistical differences for the main measures: vocabulary (all ps > .05), reading fluency (all ps > .05), and sentence dictation (all ps > .05). Half of our sample was multilingual, which is related to the multilingual situation of the geographical area in which we tested. The tests took place over 1.5 month, from May to mid-June 2021, at the end of the school year. The distribution of children by grade, their average age, their gender, and their linguistic status is presented in Table 1. This table also specifies test results by grade for general spelling and reading fluency.

Procedure

The spelling, vocabulary, and nonverbal reasoning tasks were administered to the whole class, whereas the other tests were administered individually by a researcher or by trained students in a quiet space provided by schools. For the individual tests, audio-recordings were made in order to check the children's answers for scoring. For the collective tests, the children were told to do the best they could and not to copy each other, as for a school test. At the end of the tests, the children received stickers. Double scoring was performed for 20% of the data for each experimenter. The percentage of agreement ranged from 97.3% to 99.5%. We double-checked all dictations (sentences and words), and when there were disagreements we asked a third judge, an expert of the field, to make the decision.

Materials

Receptive vocabulary

We tested children's receptive vocabulary level using the standardized EVALEO (Evaluation du Langage Ecrit et du Langage Oral) battery (Launay et al., 2018), which is a forced-choice picture–word matching test. In this computerized test, the experimenter stated a word and the children needed to choose, among four images, which one or ones corresponded to the word. For each item, a phonological distractor and a semantic distractor were included; one or two answers were possible. For example, the word "ampoule" [bulb, blister] is polysemous in French, so the children needed to choose images related to both meanings. This test was adapted to a large group; the images were projected onto the board, and the children needed to circle the answer in an answer booklet. The test included nouns, adjectives, and verbs. The test was the same from Grade 1 to Grade 3 (31 items) but it was different in Grades 4 and 5 (50 items). The Cronbach alphas provided by the test manual were α = .80 for Grade 1 to Grade 3 and α = .74 for Grades 4 and 5.

[2] REP (Réseau d'Education Prioritaire) is a French program that helps schools in socially and economically disadvantaged areas.

Table 1
Characteristics of participants and means (and standard deviations) of participant scores on the spelling and reading tests.

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Number of participants	213	252	217	231	188
Age in months	83.85	96.17	108.29	119.57	131.52
	(4.60)	(5.25)	(5.52)	(4.96)	(4.75)
Gender (% of girls)	55.87	50.40	42.86	53.25	52.66
Language status (% of multilinguals)	47.89	49.21	50.69	53.25	48.40
Spelling, standard test (L2MA; max = 50)	n/a	21.56	29.51	34.42	37.57
		(9.11)	(8.64)	(8.16)	(6.95)
Reading, standard test (EVALEO; number of words correctly read)	64.95	119.63	178.59	208.68	239.89
	(39.71)	(52.63)	(60.59)	(66.78)	(66.21)

Note. L2MA, Langage Oral, Langage Écrit battery, Mémoire, Attention; EVALEO, Evaluation du Langage Ecrit et du Langage Oral battery.

Nonverbal reasoning

Raven's progressive matrices (Raven et al., 1998) allowed us to have a measure of nonverbal reasoning. This test was also adapted to a large group. All children had a booklet with the items and needed to circle the correct answers in their booklet.

Reading

We used the standardized EVALEO battery (Launay et al., 2018) to assess text reading fluency. Children were instructed to read a meaningful text, "La Mouette" [Seagull], as quickly and accurately as possible in 2 min. We calculated the number of words correctly read in 2 min. We used this test with the sole purpose of comparing the performance level between French and Swiss children.

Phonological awareness

Deletion of initial phoneme. This standardized test came from the EVALEO battery (Launay et al., 2018). Children were asked to delete the first sound of 15 pseudowords in Grades 1 and 2, and to delete the first sound of 20 pseudowords in Grade 3 to Grade 5, to create a new pseudoword. For example, [mout] became [out]. This test gave two scores: one for time and one for accuracy. We computed a composite efficiency score in order to integrate both sets of information into a single variable: number of successful items/time. The Cronbach alpha provided by the test manual was $\alpha = .76$.

Pseudoword repetition. This test also came from the EVALEO battery (Launay et al., 2018). The examiner said 20 French-like pseudowords one after the other, and the children needed to repeat each of them immediately. The experimenter told the children before the test began that only one presentation of the pseudoword was possible during the test. An accuracy score (i.e., number of pseudowords correctly produced) was calculated. The Cronbach alpha provided by the test manual was $\alpha = .77$.

Morphological awareness

The two tests chosen were part of the standardized Morphote test (Casalis & Macchi, 2016). The tests were administered in the oral modality only.

Production task. Children needed to complete a sentence, read by the experimenter, with the correct derived word, with 12 words being prefixed and 12 being suffixed; for example, "la personne qui chasse est un ... chasseur" [the person who hunts is a ... hunter]. The Cronbach alpha ranged from $\alpha = .78$ to $\alpha = .86$ throughout the grades.

Word analogy task. Given two morphologically related words (e.g., rapide [quick]/rapidement [quickly]), the children were required to find the same association when given a third word (e.g., silence [quiet] > silencieusement [quietly]). The first 12 items were stable analogies, without phonological change of the root, and the next 12 were unstable analogies, with change of the root; for

instance, nuage [cloud]/nuageux [cloudy] . . . pluie [rain]/pluvieux [rainy]. The Cronbach alpha ranged from α = .81 to α = .90 throughout the grades.

Spelling

Inconsistent word dictation. Children were asked to write 10 inconsistent words from the standardized BALE (Batterie Analytique du Langage Écrit) test (Jacquier-Roux et al., 2010). The words were as follows: *monsieur* [məsjø] "mister," *galop* [galo] "gallop," *seconde* [səgɔ~d] "second," *ville* [vil] "city," *million* [miljɔ~], *août* [ut] "august", *femme* [fam] "woman," *parfum* [paʁfœ~] "perfume," *tabac* [taba] "tobacco" and *fusil* [fyzi] "gun". This test assessed lexical spelling skills. Children were given 1 point for each phonologically plausible word and were given 1 point if the word was spelled correctly. Students wrote the words in their booklet. The Cronbach alpha was α = .82.

Sentence dictation. The "Crow" dictation was taken from the L2MA (Langage Oral, Langage Écrit, Mémoire, Attention battery) standardized test (Chevrier-Muller et al., 1997). This test was administered to children from Grade 2 to Grade 5. Children from Grades 2 and 3 wrote only the first two sentences, whereas children from Grades 4 and 5 wrote three sentences. This test gave four different scores: one for grammatical spelling, one for lexical spelling, one for phonologically plausible spelling, and a total score. The higher a child's score, the better the child's performance. We used this test with the sole purpose of comparing the performance levels between French and Swiss children. The Cronbach alpha was α = .70.

Graphotactic test

This test was created for the current study; the rules and regularities were chosen according to previous studies as developmental guidelines (Pacton et al., 2001, 2005, 2013). Students needed to circle, between two pseudowords, the one that was the most French-like. All the pseudowords contained two syllables. We had two types of graphotactic regularities: legal versus illegal patterns, where one of the two responses was impossible (e.g., *ccirois vs. *cirrois), and another type of patterns for frequent versus less frequent items, where both responses were possible but one response was more frequent than the other (e.g., *klotir vs. *clotir). This test gave one score in accuracy. The list of the 43 pseudoword pairs is available in Appendix A of the online supplementary material. The Cronbach alpha reliability coefficients ranged from.73 to.84 in Grade 1 to Grade 5.

Data analysis

To answer our research questions, we decided to use an exploratory analysis method because there is no developmental model of lexical spelling that captures all the dimensions involved in learning to spell. We used a data-driven analysis stemming from the interaction of graph theory and inferential statistics (i.e., Gaussian graphical modeling). This is a type of network analysis that allows one to analyze and represent multivariate data in a didactic way because they are presented in the form of a relatively simple figure. This type of analysis has been widely used in scientific domains such as physics and genetics, but it is also applicable to multivariate data in psychology, especially in the literacy domain (see Colé et al., 2018; Verwimp et al., 2022) to build visual representations. A graph is represented in the form of nodes or vertices (i.e., measurements) and undirected links or undirected edges that represent the relationships between the nodes. More precisely, in our case we used a Gaussian graphical model with a lasso regularization (Glasso). The links were undirected and weighted with partial correlation coefficients to represent the potentiality of a bivariate relationship. The lasso regularization creates a sparse matrix by setting to 0 negligible links below a cutoff calculated with the EBIC (extended Bayesian information criterion) index. The strongest partial correlations are those represented by shorter links between nodes and, conversely, weaker correlations by longer links. Our data were analyzed with R Version 4.3.0 (R Core Team, 2022). We performed a data transformation with the non-paranormal transformation

implemented in the R package "huge" (Zhao et al., 2012). We then proceeded to the creation of a network composed of partial correlations using a lasso regularization (Tibshirani, 1996) associated with an EBIC (Chen & Chen, 2008) with the R package "qgraph" (Epskamp et al., 2017). Finally, we calculated the coefficient of determination (R^2) of each overall graph on lexical spelling skills and conducted a bootstrapping analysis (Efron & Tibshirani, 1986) to check the specificity of the network with the R package "bootnet" (Epskamp et al., 2018).

Results

Descriptive analysis

All raw results are shown in Table 2. Modeling of the spelling networks for each grade is presented in Fig. 1. The coefficients between the nodes on the graphs correspond to the partial correlations between the two variables. Partial correlations less than $r = .05$ were not included in the text description for the sake of brevity. Based on visual inspection, the shape of the graphs tended to specialize throughout the grades. That is, in Grade 1 all variables were related and with relatively similar coefficients. For example, the three subcomponents (morphology, phonology, and graphotactic) were linked to each other in Grade 1, whereas only morphological and phonological skills were linked in Grade 5. As the years progressed, the relationships between the variables became clearer around specific hubs until by Grade 5 lexical spelling was in a central position. Specificity indices ranged from.87 to.97 for the networks in each grade, showing good specificity of our results.

To answer our first research question, we described the links between phonological, morphological, and graphotactic skills and lexical spelling. In Grade 1 to Grade 5, spelling was directly related to all the variables that assessed each skill except production of derived words in Grade 3, which was indirectly linked to lexical spelling through the analogy task. Interestingly, the standardized indices of centrality for each variable showed that morphological skills had the most central role of this network from Grade 1 to Grade 5 (centrality = [1.09, 1.58]) in comparison with phonological skills (centrality = [−0.72, 0.87]) and graphotactic regularities (centrality = [−1.15, −0.74]).

Table 2
Means (and standard deviations) for all tests by grade level.

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Lexical spelling (max = 20)	8.16 (2.73)	11.57 (3.41)	14.14 (2.95)	15.77 (2.68)	16.98 (2.66)
Deletion task: Accuracy (EVALEO; max = 15 for Grades 1 and 2 and 20 for Grades 3–5)	8.82 (3.70)	10.35 (3.26)	14.78 (3.97)	14.66 (3.64)	14.70 (3.96)
Deletion task: Speed (EVALEO; in seconds)	83.59 (28.90)	70.23 (21.65)	90.71 (25.13)	82.04 (18.28)	75.63 (18.43)
Pseudoword repetition (EVALEO; max = 20)	12.48 (3.75)	14.33 (3.42)	15.34 (2.91)	16.41 (2.58)	16.64 (2.42)
Graphotactic regularities (max = 43)	24.46 (6.31)	29.61 (6.50)	33.36 (5.52)	34.57 (4.57)	36.03 (4.22)
Legal versus illegal patterns (max = 19)	10.54 (2.74)	12.86 (3.15)	14.50 (2.74)	15.48 (2.32)	16.33 (2.27)
Frequent versus less frequent patterns (max = 24)	13.93 (4.51)	16.75 (4.14)	18.87 (3.65)	19.09 (3.20)	19.70 (3.07)
Production task: Suffixes (Morphote; max = 24)	6.69 (3.70)	10.47 (4.77)	14.40 (4.90)	16.06 (4.48)	18.13 (3.47)
Analogy task (Morphote; max = 24)	6.49 (4.34)	10.71 (5.27)	15.18 (4.45)	16.06 (4.36)	18.23 (3.51)
Nonverbal reasoning (Raven; max = 36)	24.68 (5.44)	27.28 (5.17)	29.20 (4.23)	30.28 (3.78)	31.74 (2.83)
Vocabulary (EVALEO, max = 136 for Grades 1–3 and 168 for Grades 4 and 5)	122.61 (9.99)	127.40 (6.84)	129.12 (5.97)	147.91 (9.11)	148.93 (9.56)

Note. EVALEO, Evaluation du Langage Ecrit et du Langage Oral battery.

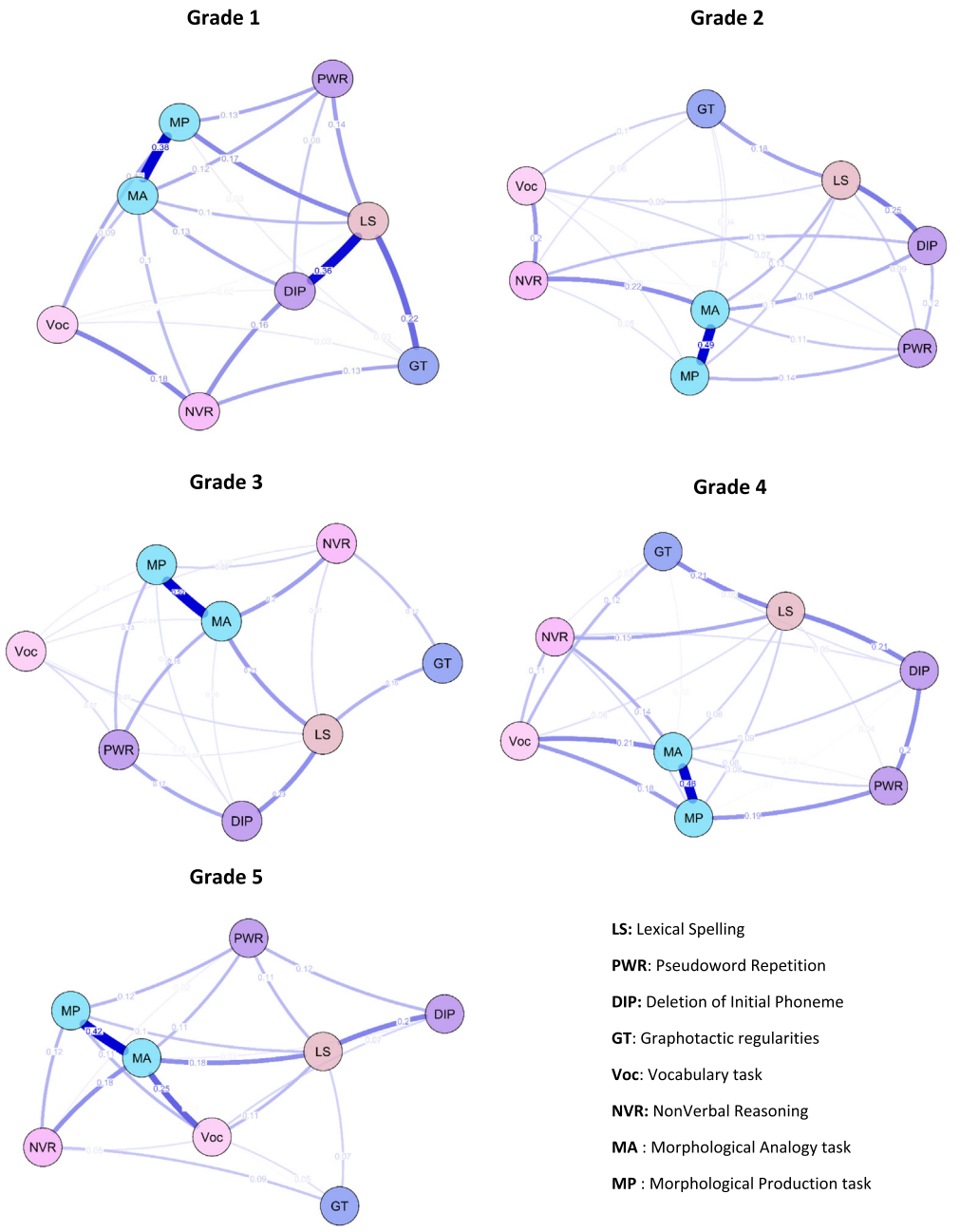

Fig. 1. Graphical representation of the lexical spelling networks from Grade 1 to Grade 5. The most connected nodes (i.e., with a high correlation coefficient) are close to each other, and the thickness of the links is a function of the correlation coefficient displayed on them. The colors used identify the dimensions evaluated. In brown: Lexical spelling. In light blue: Morphological skills. In purple: Phonological skills. In dark blue: Graphotactic regularities. In pink: Nonverbal reasoning and vocabulary. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Graph analysis

To answer our second research question, which was to establish the contribution of each skill to lexical spelling, we used the coefficients of partial correlation (r) and coefficient of determination (R^2). Note that because our sample is only transversal, the dynamic changes in partial coefficient weight and coefficient of determination are descriptive and give new hypotheses that must be formally tested in a longitudinal setting. For phonological skills, the contribution of phonological awareness,[3] with the deletion task, was seemingly high in Grade 1 (r = .36, confidence interval (CI) [.26,.47], R^2 = .127) and then appears to decrease with advancing schooling (Grade 2: r = .25, CI [.14,.37], R^2 = .065; Grade 3: r = .23, CI [.11,.35], R^2 = .052; Grade 4: r = .21, CI [.10,.33], R^2 = .046; Grade 5: r = .20, CI [.08,.33], R^2 = .040). For pseudoword repetition, the relationship was direct with lexical spelling from Grade 1 to Grade 5 (Grade 1: r = .14, CI [.02,.27], R^2 = .020; Grade 2: r = .09, CI [−.02,.20], R^2 = .008; Grade 3: r = .04, CI [−.05,.14], R^2 = .002; Grade 4: r = .04, CI [−.05,.13], R^2 = .001; Grade 5: r = .11, CI [−.01,.23], R^2 = .012), with a trend that seems to be decreasing.

As for morphological skills, in Grade 1, analogies (r = .10, CI [−.01,.21], R^2 = .011) and the production of derived words (r = .18, CI [.07,.29], R^2 = .031) had direct links to lexical spelling. In Grade 2, analogies (r = .13, CI [.02,.23], R^2 = .016) and derived word production (r = .10, CI [−.01,.21], R^2 = .009) were also directly connected to lexical spelling. In Grade 3, only the analogy test (r = .21, CI [.10,.31], R^2 = .042) was directly related to lexical spelling, and production of derived words was indirectly related via the analogy task. In Grade 4, the analogy task (r = .08, CI [−.03,.18], R^2 = .006) and derived word production (r = .08, CI [−.03,.19], R^2 = .007) were connected to lexical spelling. Finally, in Grade 5, the analogy task (r = .18, CI [.08,.29], R^2 = .034) and production of derived words (r = .10, CI [−.03,.22], R^2 = .009) were related to lexical spelling.

Concerning graphotactic skills, they were directly linked to lexical spelling from Grade 1 to Grade 5. The link between these skills appeared to remain stable from Grade 1 to Grade 4 (Grade 1: r = .22, CI [.12,.33], R^2 = .048; Grade 2: r = .18, CI [.07,.29], R^2 = .031; Grade 3: r = .16, CI [.03,.28], R^2 = .025; Grade 4: r = .22, CI [.10,.32], R^2 = .044) and then decreased from Grade 4 to Grade 5 (Grade 5: r = .07, CI [−.02,.17], R^2 = .005). For exploratory purposes, we conducted the same network analyses but with two sub-scores of graphotactic regularities: one for legal versus illegal patterns and one for frequent versus less frequent patterns. These results are presented in Appendix B of the supplementary material. They showed a direct link between lexical spelling and frequent versus less frequent patterns in Grade 1 and then a direct link only with legal versus illegal patterns from Grade 2 to Grade 5.

As for other measures, nonverbal reasoning was indirectly linked to spelling via phonological skills and morphological skills in Grade 1 and via phonological skills, morphological skills, and graphotactic regularities in Grade 2 before having a direct link in Grades 3 and 4 and then an indirect link in Grade 5 via morphological skills and graphotactic regularities. Finally, vocabulary was indirectly linked to spelling via morphological skills in Grade 1, then directly in Grade 2 to Grade 5, with stable but low coefficients from Grade 2 to Grade 4 before becoming higher in Grade 5 (r = .11, CI [−.01,.24], R^2 = .013).

Interestingly, lexical spelling was predicted by the network (considering all variables) in Grade 1 (R^2 = .375), in Grade 2 (R^2 = .287), in Grade 3 (R^2 = .229), in Grade 4 (R^2 = .261), and finally in Grade 5 (R^2 = .250). Fig. 2 shows more precisely the proportion of the variance of the lexical spelling by the three hypothesized spelling components—phonological skills, morphological skills, and graphotactic regularities—by grade to show the developmental aspect of the relative contribution of these skills.

To summarize, the contribution of phonological skills in our models was very high at the beginning of learning before decreasing as schooling progressed. The weight of graphotactic skills tended to be stable from Grade 1 to Grade 4 before decreasing in Grade 5. Finally, morphological skills increased until Grade 3 and then decreased in Grade 4 before increasing again in Grade 5. These results were confirmed by the R^2 indices (see Fig. 2), which showed that morphological skills were the only ones that increased in Grade 5.

[3] We also conducted the same network analyses with only the phonological awareness accuracy score, and the results were similar, with a smaller contribution from phonological awareness. We decided to keep the phonological awareness composite score because it remains discriminating in the highest grades (to avoid a ceiling effect).

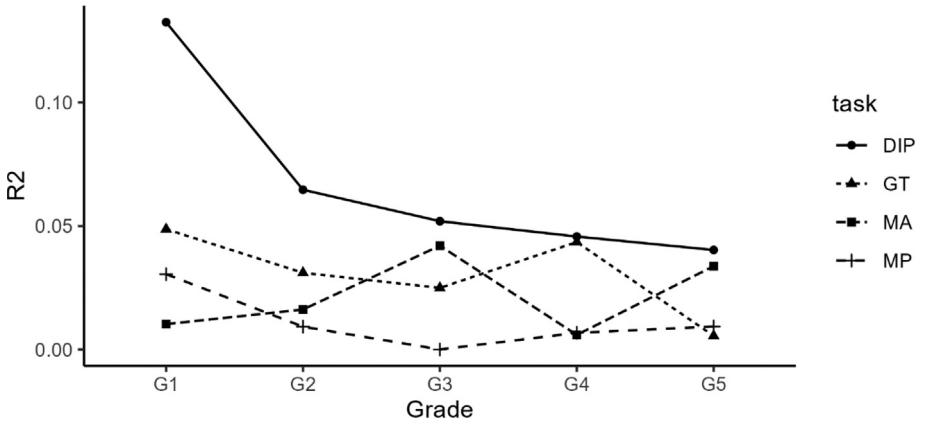

Fig. 2. Proportion of variance in lexical spelling score explained by the three spelling components: phonological skills, morphological skills, and graphotactic regularities as a function of grade. DIP, deletion of initial phoneme; GT, graphotactic regularities; MA, morphological analogy task; MP, morphological production task.

Discussion

Our research objectives were twofold: (1) to assess the involvement of phonological, morphological, and graphotactic skills in learning to spell after controlling for level of vocabulary and nonverbal reasoning and (2) to identify changes in their contribution across grade level in French-speaking primary school children. We performed network modeling to identify the skills involved in learning to spell. Our main results show a relationship between all three skills and lexical spelling from Grade 1 to Grade 5. Moreover, phonological skills were dominant in the early grades only and tended to decrease, whereas morphological skills increased until Grade 5 with a drop in Grade 4. As for graphotactic skills, they were stable from Grade 1 to Grade 4 before dropping in Grade 5. These different findings are discussed below.

Network characterization

We chose to analyze our results using an exploratory undirected network analysis in order to represent the bidirectional links between the considered variables. This kind of analysis is closer to reality given that cognitive skills are often interconnected and influence each other. For example, morphological awareness develops with exposure to the written word, and reciprocally it leads to the improvement of literacy skills (Apel et al., 2013; Levesque et al., 2021; Nunes et al., 2006). In this perspective of bidirectional links, we found a contribution of at least one task assessing each skill—phonological, morphological, and graphotactic—from Grade 1 to Grade 5, as described by several authors (Fayol, 2009; Treiman, 2017). However, it was not always the same tasks of morphological skills that were related to lexical spelling and not with the same strength. This result lends support to the hypothesis that morphological awareness is a multidimensional construct that evolves over time, hence the need to use multiple tasks to assess it (Apel, 2014; Levesque et al., 2021). Moreover, it is interesting to note that our graphotactic measure remained linked to lexical spelling at all grades; therefore, it seems relevant to include different graphotactic regularities (Pacton et al., 2001, 2005) to embrace this complex skill.

One interesting result is that only morphological skills increased its link with lexical spelling skills in Grade 5 (for both tasks). This result goes hand in hand with the hypothesis that morphological knowledge plays an increasingly important role in the learning of spelling with the advancement of schooling, concomitantly with a decrease in the weight of phonological skills. Once the phoneme–grapheme correspondences have been learned, by the end of elementary school we can expect that there

will no longer be enough inter-individual differences at this age, reducing its contribution to the total variance. Two *meta*-analyses have shown, for example, that the effectiveness of phonics interventions on reading and spelling tends to decrease with advancing schooling in favor of morphology interventions (Galuschka et al., 2020; Suggate, 2010). Similarly, for graphotactic regularities, it can be assumed that children reach a plateau in their sensitivity to written language, at least for the basic regularities tested with our task.

More specifically, when we looked at the evolution of the networks for the three skills, we noted that phonological awareness was closely related to morphological awareness at the beginning of learning, suggesting that they are at least based on the same general analytic skills, as mentioned in several studies, but also based on specific skills and or representations (Casalis & Louis-Alexandre, 2000; Inoue et al., 2023; Lee et al., 2022). For morphological awareness, we noticed that the two variables we assessed were directly related to each other. The analogy task appeared to be an important hub given that all the other tasks were linked to it (Inoue et al., 2023). The variables that assessed morphological awareness were also related to vocabulary level. This relationship became more important in Grades 4 and 5. These results are consistent with previous studies showing the link between morphological awareness and vocabulary, especially in the secondary grades (Inoue et al., 2023; Lee et al., 2022). However, graphotactic skills were linked to phonological and morphological skills in Grade 1 before becoming well-dissociated skills in Grade 5.

Weight of connections between related skills and lexical spelling

When considering the weight of the connections related to lexical spelling, we expected phonological skills to be the most important at the beginning of learning for lexical spelling (Treiman, 2017). Indeed, when children need to spell a word, even if it is inconsistent, they can use their phonological skills at least partially. Our results show that children appear to use their phonological skills to spell words until Grade 5, when mastery of matching rules is sufficient to add other skills such as morphological skills. These latter skills were linked to lexical spelling as early as Grade 1 and remained linked throughout elementary school. Their contribution was not the most important to spelling, but it remained present in an increasing way, with a drop in Grade 4. These results provide further support for the hypothesis that morphology plays an early role in learning to spell in addition to phonological skills (Ardanouy et al., 2024; Bowers & Bowers, 2017; Desrochers et al., 2018). Bowers and Bowers (2017) recommended that morphological skills should be taught in combination with phonological skills as early as Grade 1 because morphology makes spelling more transparent. These recommendations have been made for English but are also applicable to French. As suggested by Galuschka et al. (2020) and our own results, morphological analysis instruction can be effective as early as Grade 1. Finally, an interesting feature of morphological skills is that the variables that assess them show both decreases and increases and not a linear trend. This may suggest a link with spelling progression, which is not always linear either; children use the knowledge they have at their disposal at the time of learning, with the possibility of stagnation, regression, or improvement (Fayol et al., 2020; Houdé & Borst, 2022).

Very few studies have explored the role of graphotactic regularities in relation to other skills and to lexical spelling (Pacton & Deacon, 2008; Pacton et al., 2005). Hence, one important aspect of our study was to do just that, namely measure the role of graphotactic regularities in lexical spelling. We found an impact of graphotactic regularities as early as Grade 1 (as in Pacton et al., 2001, and Treiman & Kessler, 2006), which was stable until Grade 4 and then decreased in Grade 5. More precisely, the contribution of graphotactic regularities remained stable until Grade 4, before being supplemented by morphological skills that were more important in Grade 5. The impact of both skills was expected given that Pacton et al. (2005) showed that the use of graphotactic regularities for the spelling of word endings (e.g., ‘‘-ette,’’ ‘‘-eau’’) remains present even when the use of morphological rules is possible. More specifically, legal versus illegal graphotactic patterns seem to play a predominant role from Grade 2 to Grade 5, as if frequent versus less frequent patterns came into play only at a later stage during primary school. The direct link found in Grade 1 between frequent versus less frequent graphotactic patterns and lexical spelling can be moderated because many children scored below 50% at a descriptive level for this task in this grade (37% for the legal vs, illegal score and 29% for the frequent

vs. less frequent score). Furthermore, the performance between legal versus illegal and frequent versus less frequent patterns is quite similar across the five grades. One possible explanation is that some regularities apply to only a small number of words (e.g., words can begin with "con" but not "quon"), whereas others apply to a larger number of words (e.g., the illegality of doublets in the word-initial position). This could also explain why we do not observe a better mastery of legal versus illegal patterns compared with frequent versus infrequent patterns, as suggested in the literature (Pacton et al., 2001).

Given the important role of graphotactic regularities in our results, it would be interesting to provide interventions that target this knowledge, which is implicitly learned in typically developing children, in order to accelerate their learning. Some studies have already shown the interest of carrying out such interventions on orthographic knowledge (Galuschka et al., 2020; Squires & Wolter, 2016). However, the definition of orthographic knowledge is not identical to that of graphotactic regularities because orthographic knowledge combines the graphical mental representation of a word and the orthographic patterns (Apel, 2011). These patterns are decomposed into alphabetic knowledge, letter rules that can be associated, and orthotactic rules about the position and context of the use of certain letters. Graphotactic regularities can be assimilated to the last component of orthographic patterns. Therefore, it would be worthwhile to offer an intervention targeting this specific skill of graphotactic regularities, particularly on the most frequent regularities that have the fewest exceptions (where generalization therefore is maximal).

Our results support the idea that IMP learning theory can explain the process of learning to spell words (Treiman & Kessler, 2014). Due to the simultaneous interaction of phonology, morphology, and graphotactic regularities, children can spell words, using these skills in different ways depending on the word they need to write but also depending on how far they have progressed in their schooling and therefore in their knowledge of written language.

Limitations and perspectives

One limitation of our study is that we conducted a cross-sectional study and not a longitudinal one. Therefore, we cannot be sure that the phonological, morphological, and graphotactic skills would evolve in the same way in the same sample of children followed longitudinally from Grade 1 to Grade 5. The nonlinear trends in our study may be confused with random fluctuations due to the fact that the samples were cross-sectional and not longitudinal (possible measurement error). Thus, this study needs to be replicated using a longitudinal design but also with confirmatory analyses to support our results, given the exploratory nature of our analyses. Moreover, offering the same tests to children from Grade 1 to Grade 5 is a very difficult task if the sensitivity of the test is to be maintained. A solution for future research would be to have more items of increasing difficulty per test with a stopping rule, but also to have response times for all tasks in addition to accuracy scores. For this reason, we may wonder whether the tendency to obtain ceiling effects, confirmed by depressed Cronbach coefficients, on certain tasks in Grade 5 might have had an effect on the final results. Specifically, it is important to remember that phonological awareness has a measure of time and accuracy, whereas morphological awareness and sensitivity to graphotactic regularities only take accuracy into account. The importance of phonological awareness therefore may have been overestimated in relation to the other two components. Furthermore, following the same principle, we needed to use a vocabulary test in which the items were different between Grades 1 to 3 and Grades 4 and 5, which implies that the interpretation of the differences between groups should be made with caution with respect to this variable. Next, the graphotactic task would need to be improved to always select legal bigram pairs in French. Indeed, it is not enough to carefully select the tested graphotactic regularity; close attention also needs to be paid to the rest of the pseudoword, ensuring that it consists only of legal letter sequences in French. In our case, 2 pairs of words out of 43 contained illegal bigrams. Finally, future studies could test the specificity of the links between morphological awareness, sensitivity to graphotactic regularities, and lexical spelling using several types of items: (1) words for which morphological information can be used (e.g., chevreau [baby got] with the suffix "-eau") versus (2) words for which morphological information cannot be used (e.g., cerveau [brain]) [but with no difference in terms of graphotactic regularities for (1) and (2)]; and (3) words including frequent graphotactic patterns

(e.g., clavier) versus (4) words including less frequent graphotactic patterns (e.g., klaxon) [but with no possibility to rely on morphological information for (3) and (4)].

Conclusion

This study highlighted the role of three different skills—namely phonological skills, morphological skills, and graphotactic regularities—for learning lexical spelling during elementary school. Phonological skills were the most important before reaching a celling as all children progressively master the phoneme–grapheme rules. From a certain age onward (end of elementary school), inter-individual differences decrease, leading to a weaker relationship with other skills, but phonological skills obviously remain a fundamental skill underlying spelling performance even in adulthood. Graphotactic regularities were important in learning to spell. This type of knowledge tends to be underestimated and has been less frequently studied in the literature than morphological skills, but our results suggest that it was equally important in learning to spell. Exposure to the written language through implicit learning leads to significant statistical learning of spelling rules. Finally, morphological skills were the only domain that increased at the end of Grade 5, to reach the level achieved in Grade 3, which confirms its crucial role in learning to spell, particularly in the higher grades. Based on our findings, we recommend the teaching of these three different skills, and particularly the teaching of morphological skills, in early primary school to facilitate the development of spelling.

CRediT authorship contribution statement

Estelle Ardanouy: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elise Lefèvre:** Writing – review & editing, Formal analysis. **Hélène Delage:** Writing – review & editing, Validation, Supervision, Conceptualization. **Pascal Zesiger:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2024.105963.

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