Do serial order short-term memory and long-term learning abilities predict spelling skills in school-age children?

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Laura Ordonez Magro [a,b], Steve Majerus [e], Lucie Attout [e], Martine Poncelet [e], Eleonore H.M. Smalle [d], Arnaud Szmalec [a,c,d]

[a] Psychological Sciences Research Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[b] Laboratory of Cognitive Psychology, CNRS and Aix-Marseille University, Marseille, France
[c] Institute of Neuroscience, Université catholique de Louvain, Louvain-la-Neuve, Belgium
Place Cardinal Mercier, 10
1348 Louvain-la-Neuve, Belgium
E-mail: arnaud.szmalec@uclouvain.be
[d] Department of Experimental Psychology, Ghent University
Henri-Dunantlaan, 2
9000 Ghent, Belgium
E-mail: eleonore.smalle@ugent.be
[e] Psychology and Neuroscience of Cognition Research Unit, Université de Liège
Boulevard du Rectorat, 3 (B33)
4000 Liège, Belgium
E-mail: lucie.attout@uliege.be; smajerus@uliege.be

Correspondence Address

Laura Ordonez Magro

Laboratory of Cognitive Psychology, Aix-Marseille University

3 Place Victor Hugo

13331 Marseille, France

E-mail: laura.ordonezmagro@gmail.com

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Abstract

Compared to most human language abilities, the cognitive mechanisms underlying spelling have not been as intensively investigated as reading and therefore remain to this day less well understood. The current study aims to address this shortcoming by investigating the contribution of serial order short-term memory (STM) and long-term learning (LTL) abilities to emerging spelling skills. Indeed, although there are several reasons to assume associations between serial order memory and spelling abilities, this relationship has hardly been investigated empirically. In this study, we hypothesized that serial order STM plays an important role in spelling novel words, for which children are supposed to rely on a sequential nonlexical spelling procedure. Serial order LTL was hypothesized to be involved in the creation of more stable orthographic representations allowing children to spell (regular and irregular) words by using a lexical spelling strategy based on the direct access to orthographic representations stored in long-term memory. To assess these hypotheses, we conducted a longitudinal study in which we tested a sample of 116 French-speaking children at first grade and two years later at third grade of primary school. At first grade, we administered tasks that were specifically designed to maximize STM and LTL abilities for serial order information. At third grade, we assessed spelling abilities using irregular word, regular word, and pseudoword writing-to-dictation tasks. Bayesian regression analyses showed that pseudoword, but also irregular word spelling was best predicted by serial order STM, while regular word spelling was similarly predicted by both serial order STM and LTL.

Keywords: Short-term memory; Long-term learning; Serial order; Spelling

1. Introduction

While there has been intense research interest in how children learn to read, the mechanisms involved in spelling acquisition are less well understood. At the same time, studies exploring serial order short-term memory (STM) and long-term learning (LTL) abilities have provided some understanding of the mechanisms that are involved in reading acquisition. Based on the assumption that written language is a sequential process (Houghton et al., 1994; Peressotti & Grainger, 1995, 1999; Whitney, 2001), recent studies have shown that reading acquisition is governed by (1) the ability to temporarily maintain serial order information in STM (i.e., serial order STM ability) (Binamé & Poncelet, 2016a, 2016b; Hachmann et al., 2014; Holmes, Malone, & Redenbach, 2008; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2012, 2013; Martinez Perez, Poncelet, Salmon, & Majerus, 2015; Romani, Tsouknida, & Olson, 2015; Whitney & Cornelissen, 2005) and (2) the ability to consolidate serial order information in long-term memory (i.e., serial order LTL ability) (Bogaerts, Szmalec, De Maeyer, Page, & Duyck, 2016; Bogaerts, Szmalec, Hachmann, Page, & Duyck, 2015; Smalle et al., 2019). Note however that the observation of a link between serial order memory and reading development does not necessarily imply that serial order memory is systematically affected in (all) persons with reading disabilities such as dyslexia. While an increasing number of studies on persons with dyslexia observe serial order memory deficits (Bogaerts et al., 2015; Hachmann et al., 2014; Majerus & Cowan, 2016; Martinez Perez, Majerus, Mahot, et al., 2012; Romani et al., 2015; Schraeyen et al., 2017, 2019; Szmalec et al., 2011), , a specific deficit is not always observed (Schmalz et al., 2019; Staels & Van den Broeck, 2014, 2015; van Witteloostuijn et al., 2019; West et al., 2019; see also Majerus & Cowan, 2016 for a review).

Contrary to reading, only few studies have investigated the involvement of serial order STM in spelling acquisition and no study has been conducted to investigate how serial order LTL mechanisms may contribute to emerging spelling skills. In the present study, we addressed these questions by examining whether and how serial order STM and LTL abilities predict spelling performance.

Learning to spell first requires learning the sound-spelling correspondences. Moreover, experience with print will allow spellers, even young ones, to quickly acquire semantic as well as morphological knowledge about the orthography of their language. Indeed, they will for instance rely on the meaning of words to figure out how to spell related words (e.g., relying on *courage* to spell *courageous*). They will also learn specific properties of their orthography such as knowing that English words can end but not start with double consonants or that letters such as “s” can double but not letters like “a” (Treiman & Bourassa, 2000; Treiman & Cassar, 1997). It is also well established that learning to spell is more arduous than learning to read, especially in opaque/deep writing systems such as English or French (Bosman & Van Orden, 1997). Indeed, there exists an evident asymmetry between spelling and reading in these languages. In French, there is for instance only one way to read the phoneme “eau”, which sounds /o/, but /o/ can be mapped onto more than one grapheme such as “o”, “au”, “eau”, etc. This property leads to the manifestation of many spelling errors, even in experienced spellers, errors that are however mostly phonetically accurate (e.g., writing *batau* instead of *bateau* in French or *Klinton* instead of *Clinton* in English) (Bosman & Van Orden, 1997).

It appears in the literature, that several theoretical spelling models (Brown & Loosemore, 1994; Ellis & Young, 1988; Houghton & Zorzi, 2003; Loosemore, Brown, & Watson, 1991) are adaptations of *dual-route models of reading* (e.g., Forster & Chambers, 1973). Similar to dual-route models of reading, spelling models assume the existence of two distinct spelling procedures: a lexical spelling route allowing to spell familiar words based on the direct access to their orthographic representations stored in the mental lexicon, and a nonlexical route allowing to spell unfamiliar words by proposing a phonologically plausible production of the word based on dominant phoneme-to-grapheme correspondences (e.g., writing “f” rather than “ph” to represent the phoneme /f/). The conceptualization of a dual-route model in spelling is supported by neuropsychological data of adults with acquired dysgraphia showing a double dissociation between patients that suffered from a selective impairment of the lexical route (Rapp, Epstein, & Tainturier, 2002) and other patients showing a selective impairment of the nonlexical route (Shallice, 1981). Nevertheless, the strict independence of both spelling procedures has been questioned by some studies observing that lexical and nonlexical routes do interact during spelling, in healthy as well as in brain-injured adults (Miceli, Capasso, & Caramazza, 1994; Rapp et al., 2002; Seymour, 1988). The idea of a parallel activation of both routes during spelling is supported by a more recent dual-route connectionist model proposed by Houghton and Zorzi (2003). In this model, the lexical and the nonlexical routes are activated in parallel and the final spelling is determined by the combined output of both routes. Furthermore, according to a large number of behavioral (Holmes & Babauta, 2005), neuropsychological (Tainturier & Rapp, 2001), and functional neuroimaging studies (Purcell, Jiang, & Eden, 2017; Rapcsak et al., 2003), as well as data on developmental dyslexia and dysgraphia (Curtin, Manis, & Seidenberg, 2001), it is nowadays widely assumed that reading and spelling rely on a common orthographic lexicon (Rapcsak, Henry, Teague, Carnahan, & Beeson, 2007). This implies that reading and spelling can access shared orthographic representations and that, as a consequence, reading and spelling performance affect each other in the sense that creating orthographic representations through reading experience may allow to improve spelling acquisition, and spelling acquisition in turn may allow to strengthen reading performance (Ahmed et al., 2014; Ellis, 1994; Rapp & Lipka, 2011).

In sum, it appears that reading and spelling acquisition are closely related processes that share several functional characteristics, which has led to the development of similar cognitive architectures for both skills. However, the exact mechanisms underlying reading and especially spelling are hardly specified in these models. To get a better understanding of these mechanisms, recent work has focused on the sequential nature of written language (Binamé & Poncelet, 2016; Bogaerts et al., 2016, 2015; Holmes et al., 2008; Houghton et al., 1994; Martinez Perez, Majerus, & Poncelet, 2012; Romani et al., 1999; Romani et al., 2015; Szmalec et al., 2011; Whitney, 2001). When reading a novel word, one has to translate each grapheme into its corresponding phoneme and to temporarily maintain these phonemes in their exact serial position until the entire word has been processed. Finally, these phonemes have to be assembled for pronunciation, again in their correct order. Repeating this decoding activity then allows the creation of a unified, more stable long-term orthographic representation of the letter sequence. Similar to reading, spelling also appears to be sequential in nature. Indeed, spelling a word comes down to translating each phoneme into its corresponding grapheme, to temporarily maintain these graphemes in their correct serial position in order to keep track of which phonemes have already been converted, before finally producing the written word with all graphemes in their correct serial order (Romani et al., 2015). One of the reasons for this strong reliance on the processing and representation of serial order information is the fact that alphabetic writing systems, being constituted of a limited set of letters, are particularly prone to the formation of anagrams (i.e., words that are constituted of the same letters, but in different orders, e.g., *stop, spot, tops, post*). Confounding the order of letters composing such anagrams indeed can lead to the production of a word with a different meaning (e.g., *stop* instead of *spot*). Some models have attempted to describe the sequential mechanisms that are involved in spelling activities (Caramazza & Miceli, 1990; Houghton et al., 1994). According to the *Competitive Queuing model* proposed by Houghton et al., spelling is governed by a gradient of activation making sure that activation is stronger for the first letter to be produced as compared to the following ones. As soon as a letter has been written down, it is inhibited and activation feeds forward to the next letter, and so on until the last letter has been written down. This sequential treatment is accomplished in the so-called graphemic buffer, a working memory subsystem that allows to maintain the orthographic information active before and during written production (Caramazza & Miceli, 1990). This model is also able to explain the order errors (letter movements e.g., SPRINT > SRINTP and transpositions e.g., SPRINT > SNRIPT) that are frequently observed in persons with dyslexia (Romani et al., 2015) and acquired dysgraphia (Caramazza, 1988; Schiller, Greenhall, Shelton, & Caramazza, 2001). The current study focuses on the development of spelling skills in French. Just like English, French has an opaque orthography, especially in the spelling direction (for instance, a monosyllabic French word has 3,67 spelling alternatives on average (Ziegler et al., 1996)). When children have to deal with numerous irregularities, it is not surprising that reading and spelling activities are closely related to memory functioning, which is thus especially true for opaque orthographies, such as in English or French (Demoulin & Kolinsky, 2016).

Recent studies have revealed an association between the ability to retain serial order information in STM and reading performance in healthy and impaired children and adults (Binamé & Poncelet, 2016; Hachmann et al., 2014; Holmes et al., 2008; Martinez Perez, Majerus, Mahot, et al., 2012; Martinez Perez, Majerus, & Poncelet, 2012; Martinez Perez et al., 2013; Nithart et al., 2011; Romani et al., 2015). These studies are based on recent verbal STM models making a distinction between the short-term retention of *item* (i.e., the identity of the items) versus *serial order* (i.e., the serial order amongst these items) information (Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999, 2006; Gupta, 2003, 2006; Gupta & MacWhinney, 1997; Henson, 1998; Majerus, 2009). The retention of item information has been shown to be affected by language knowledge such as (sub)lexical and semantic knowledge, while the recall of serial order information is much less influenced by this knowledge (Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1996; Saint-Aubin & Poirier, 2005). In accordance with these findings, the association between item STM and reading measures is likely to reflect the common reliance on preexisting language knowledge. Making a distinction between STM for item versus serial order information allows to estimate the specific and language-independent contribution of serial order STM to linguistic functions. By using tasks maximizing either item or serial order STM requirements, a number of authors have observed that serial order STM, but not item STM, was able to predict later reading skills, providing evidence that reading is especially supported by the ability to encode serial information in STM (Binamé & Poncelet, 2016b; Martinez Perez, Majerus, & Poncelet, 2012; Nithart et al., 2011). Some of these studies also showed impaired serial order STM performance in persons with dyslexia as compared to matched controls, indicating that an impairment in serial order STM ability might hinder reading acquisition (Hachmann et al., 2014; Majerus & Cowan, 2016; Martinez Perez et al., 2015; Martinez Perez, Majerus, et al., 2013; Martinez Perez, Majerus, Mahot, et al., 2012; Romani et al., 2015; Schraeyen et al., 2017, 2019).

However, only a handful of studies have investigated the link between serial order STM and spelling performance. In 1999, Romani, Ward, and Olson observed impaired serial order STM ability in adults with dyslexia suffering not only from reading difficulties, but also from severe spelling disabilities. More recently, Lervåg and Hulme (2010) found that serial order STM measured in kindergarten children predicted later nonword spelling skills. Five years later, Romani et al. (2015) corroborated these results by showing significant correlations between serial order STM and spelling performance in skilled spellers. Finally, in a study involving 204 typically developing children from second to sixth grade of primary school, Binamé and Poncelet (2016a) observed that serial order STM predicted the speed at which children were able to form novel orthographic representations in an orthographic learning task. These authors further investigated this link more closely in a longitudinal study involving beginning spellers (Binamé & Poncelet, 2016b). Their findings revealed that serial order STM performance tested in kindergarten predicted nonword spelling capacity measured one and two years later i.e., at first and second grade. Interestingly, they found no significant correlation between serial order STM and the spelling of familiar and irregular words. In the light of these results, the authors concluded that serial order STM may stop being implicated in spelling as soon as long-term orthographic representations become available and allow the use of a direct lexical spelling strategy.

Regarding the implication of serial order LTL in spelling, there is, to the best of our knowledge, no study that has reported on this link in the literature. However, as spelling, to some extent, shares its cognitive underpinnings with reading, we will briefly expose what we currently know about the contribution of serial order LTL to reading. Several studies revealed an association between serial order LTL and reading performances in healthy and reading impaired children and adults (Bogaerts et al., 2016; Bogaerts et al., 2015; Szmalec et al., 2011). In these studies, serial order LTL performance was measured using a Hebb repetition task inspired by Donald Hebb's seminal *Hebb repetition learning paradigm* (Hebb, 1961). In this paradigm, participants perform an immediate verbal serial recall task of repeating (Hebb) sequences and non-repeating (filler) sequences of nine digits, with the Hebb sequence being repeated on every third trial without the participant knowing. Hebb observed that the recall of repeated sequences gradually increases as compared to the non-repeating sequences, an observation which is better known as the Hebb repetition effect. In their longitudinal study, (Bogaerts et al., 2016) tested children at first and second grade of primary school on Hebb repetition and reading tasks. They observed an association between serial order learning capacity and reading ability as well as weaker serial order learning in poor readers compared to more skilled readers. Regarding impaired readers, Szmalec et al. (2011) and (Bogaerts et al., 2015) reported that adults with dyslexia show impaired performance in Hebb repetition tasks compared to controls (but see Staels & Van den Broeck, 2015). Based on these observations, the authors suggest that serial order learning mechanisms play an important role in the creation of long-term orthographic representations. These studies together highlight the importance of serial order LTL in reading. In the present study, we adopted this serial order memory framework to investigate whether, and if so, to what extent serial order LTL is associated to spelling ability.

We used a longitudinal design with 116 primary school children, who we tested with serial order STM and LTL tasks at first grade and with spelling-to-dictation tasks at third grade. We measured serial order STM ability with a serial order reconstruction task designed and validated by Majerus, Poncelet, Greffe, and Van der Linden (2006). Given that no serial order STM task can be considered to be completely pure, we controlled for item STM ability by using a single nonword delayed repetition task (item STM) also validated in previous studies (e.g., Attout & Majerus, 2015; Attout, Noël, & Majerus, 2014; Leclercq & Majerus, 2010; Majerus & Boukebza, 2013; Majerus, Poncelet, Greffe, et al., 2006; Martinez Perez, Majerus, & Poncelet, 2012; Ordonez Magro, Attout, Majerus, & Szmalec, 2018). Serial order LTL was assessed with an adaptation of the Hebb repetition learning task involving consonant-vowel (CV) syllables as used in previous studies (Smalle et al., 2016; Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). Spelling abilities were tested at third grade via the administration of the writing-to-dictation subtest of irregular words, regular words, and pseudowords which are part of the French standardized written language battery “Batterie Analytique du Langage Écrit” ("BALE", Jacquier-Roux, Lequette, Pouget, Valdois, & Zorman, 2010). We hypothesized that serial order STM would predict pseudoword spelling because this memory structure allows to maintain the constituent graphemes in STM during the phoneme-to-grapheme conversion process (nonlexical spelling route). Serial order LTL was hypothesized to be involved in the creation of more stable, long-term orthographic representations, presumably through Hebb repetition learning mechanisms. We therefore predicted that Hebb learning performance would be particularly associated with the spelling of regular and irregular words, which are known words that in the course of spelling acquisition become accessible through a more direct lexical spelling strategy.

2. Method

2.1 Participants

A total of 131 typically developing French-speaking children were involved in our study. We tested them at the end of first grade (M_{age} = 81 months, SD = 3.56; 63 girls) and again at the end of third grade (M_{age} = 105 months, SD = 3.52; 60 girls). The current analyses were performed on a sample of 116 participants, due to a drop-out of 15 children between first and third grade. Note that performance on all tasks measured at first grade did not significantly differ between children who dropped out of the study and those who completed both assessments. This indicates that the cognitive profile of the children who left school over the duration of the longitudinal study, did not differ from the profile of the children who participated to all testing sessions. Our sample was recruited in nine primary schools within the region of Walloon Brabant in Belgium. Parents received a written description of the study as well as a parental and anamnestic questionnaire, which allowed us to ensure that the children were French-speaking monolinguals without a history of neurological disorder, neurodevelopmental delay, sensory, or learning impairments. Only the children for whom we obtained parental consent participated in this study. All children came from families with middle-class socioeconomic background. They participated voluntarily in this study and parental consent was obtained for each child. The study had been approved by the ethics committee of the Faculty of Medicine at the University of Liège under the project name Order Memory and Language development (protocol number 2014-295).

2.2 Materials and procedure

2.2.1 Tasks administered at first grade

2.2.1.1 Order short-term memory task (Animal Race task)

This task was an adaptation from the serial order reconstruction task designed and validated by Majerus, Poncelet, Greffe, et al. (2006). It was created to maximize the short-term retention of serial order information, while minimizing item STM requirements. Participants were instructed to listen to sequences of two to seven animal names (chat, chien, coq, lion, loup, ours, singe [cat, dog, cock, lion, wolf, bear, monkey, respectively]) and they then had to rearrange cards with the depicted animals in the order of presentation. As not all animals were used on each trial, the experimenter provided participants only with the animal cards that were part of the to-be-recalled sequence. The animal names were announced through headphones at a rate of one item per second. To render the task more playful, we told the children that we would play an animal race game. The children were asked to arrange the cards with the depicted animals on a podium with seven steps, drawn on a sheet, in the order they crossed the finishing line. Participants had only to recall the serial order of the sequences, given the fact that the items constituting the sequence were available during recall, and thus, item retention capacity was minimized. The animal names were all monosyllabic, highly familiar and of low age of acquisition, which further allowed reducing item information processing requirements. For reasons of time constraints, we reduced the number of trials per length from four to three trials, relative to the original version of the task (see also Ordonez Magro et al., 2018). The serial order STM score was computed based on a method introduced by McKelvie (McKelvie, 1987). This method takes into account both the absolute and relative position of the recalled items. In a first step, the number of items recalled in correct position from left to right up to the first error is determined. In a second step, the same procedure is applied from right to left. In a third step, the number of items recalled in any correct sequence of two or more syllables between the first error from the left and the first error from the right is counted. Finally, any other item that occurs in the correct absolute position (independent from its relative position) from left to right is counted. Taking the example “chat coq chien ours singe loup lion” recalled as “chat chien ours loup singe coq lion”: “chat” would be scored as one item correct

(.12) in step 1, “lion” would be scored as one item correct (.12) in step 2, “chien ours” would be scored as two items correct (.25) in step 3, and “singe” would be scored as one item correct (.12) in step 4, as it is recalled in its correct absolute position, even though, relative to its neighbors “ours” and “loup”, it is not recalled in the correct position. This would yield a total score of .61, which serves as the dependent variable.

2.2.1.2 Item short-term memory task (Princess task)

This task was also an adaptation from Majerus et al. (2006) and was designed in order to maximize the short-term retention of item information, while minimizing serial order STM requirements. In this task, participants had to listen to monosyllabic CVC nonwords (e.g., “dub”) presented one at a time through headphones. To ensure that the to-be-recalled nonword was correctly perceived, children had first to recall it immediately after its presentation. Subsequently, participants had to repeatedly produce the syllable “bla” for a total of 3 seconds. This allowed blocking articulatory rehearsal and thus, preventing sequential processing of the phonemes representing the item. Participants were finally required to recall the initially presented nonword (i.e., “dub”), allowing us to measure item retention abilities. This task was also presented as a game. We told children that they were a princess (for a girl) or an adventurer (for a boy) and that they had to remember magic passwords (i.e., the nonwords) to open 20 doors in order to escape from a castle. Order information retention capacity was minimized, because only one single monosyllabic nonword had to be recalled at a time. Additionally, item STM requirements were maximized by using nonwords with a CVC structure and with low diphone frequencies relative to the phonological structure of French (Tubach & Boe, 1990). Again, in order to save time, our adapted task consisted of 20 nonwords instead of 34 in the original task (see also Ordonez Magro et al., 2018). We determined the number of correctly repeated phonemes as the dependent variable, which gave us a maximum score of 60.

2.2.1.3 Hebb repetition learning task

Children were required to verbally recall sequences of six nonsense CV syllables immediately after their auditory presentation. In case they forgot one item among the six syllables, they were allowed to say “blanc” (“blank” in English) and to continue recall. We did not make participants aware of the fact that one sequence, the Hebb sequence, was repeated every second trial, while the other (filler) sequences contained random syllable successions. We used six syllables per sequence: the mean digit span (which is of 4) in 6-year-olds + 2 (Case, Kurland, & Goldberg, 1982; Dempster, 1981). Using supra-span sequences allows us to provide room for progression through repetition learning. Similarly to Mosse and Jarrold (2008), we used a non-overlapping design between both types of sequences, which means that the filler sequences were constructed of different syllables compared with the Hebb sequences. Both sets of syllables were matched for diphone frequency by using the French database of diphone frequency “Diphones-fr” (New & Spinelli, 2013). We used the WordGen software to match all sequences according to their summed diphone frequency (see Table 1; Duyck, Desmet, Verbeke, & Brysbaert, 2004). Additionally, we created our sequences by ensuring that two or more consecutive syllables never resulted in an existing French word (e.g., SO NA could remind the child of “sauna”). We presented 18 sequences (9 repetitions of the Hebb sequence, interspersed with 9 filler sequences) to each participant. The syllables were prerecorded by a female voice and presented one at a time through headphones with an inter-stimulus interval of 100 ms. To familiarize children with the task and to ensure that they correctly perceived the items, we always began by asking them to repeat each syllable three times after the experimenter. Before starting the learning phase, the children were required to recall one filler sequence, which served as a practice trial. Filler and Hebb sequences were presented alternatively as followed: f, H, f, H, f, H, f, H, f … Hebb scores were computed based on a method introduced by McKelvie (McKelvie, 1987; Ordonez Magro et al., 2018, 2020; Smalle et al., 2016; Smalle, Page, Duyck, Edwards, & Szmalec, 2017; Staels & Van den Broeck, 2015), which we have explained in detail in the section dedicated to the serial order STM task. In this task, as an example, the sequence “da lu fi pa ve ti ro mi” recalled as “da po fi ve ti mi”: “da” would be scored as one item correct (.12) in step 1, “mi” would be scored as one item correct (.12) in step 2, “ve ti” would be scored as two items correct (.25) in step 3, and “fi” would be scored as one item correct (.12) in step

4, as it is recalled in its correct absolute position, even though, relative to its neighbors “lu” and “pa”, it is not recalled in the correct position. This would yield a total score of .61.

Table 1.

Stimulus material for the Hebb tasks at first grade. French diphone frequency for each syllable is reported.

Filler		**Hebb**	
CV	**Diphone**	**CV**	**Diphone**
TI [ti]	3440	RI [ʁi]	3880
PA [pa]	1755	MI [mi]	1670
FI [fi]	1142	NA [na]	1262
VE [və]	50	BE [bə]	29
DA [da]	497	GU [gy]	173
LU [ly]	615	SO [sɔ]	492

2.2.1.4 Receptive vocabulary knowledge

In order to measure receptive vocabulary knowledge, we used the EVIP scale (Dunn, Theriault-Whalen, & Dunn, 1993), which is the French adaptation of the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981). Raw vocabulary scores were used for analyses.

2.2.1.5 Nonverbal intelligence

To control for nonverbal intelligence, we used Raven’s Progressive Colored Matrices (Raven, Court, & Raven, 1998). Raw scores were used for the analyses.

Estimates of vocabulary knowledge and nonverbal intelligence were collected to ensure that our participant sample was homogeneous with respect to receptive vocabulary and nonverbal intelligence abilities, and that no participant showed developmental delay or cognitive impairment.

2.2.2 Task administered at third grade

2.2.2.1 Writing-to-dictation task

We measured (pseudo)word spelling by using the writing-to-dictation subtest of the standardized written language battery “Batterie Analytique du Langage Écrit” ("BALE", Jacquier-Roux, Lequette, Pouget, Valdois, & Zorman, 2010). This task consists of monosyllabic, disyllabic, and trisyllabic words which are selected from the Dubois-Buyse scale (Ters et al., 1940). The task contains 10 irregular words, 20 regular words, and 20 pseudowords. Jacquier-Roux et al. made sure to choose words for which the spelling is commonly mastered between six and twelve years of age. The words from the three lists are matched for the number of phonemes (mean = 4.1 phonemes) as well as for frequency (standard frequency index = 59.3 for regular words, 60.2 for irregular words, and 58.2 for pseudowords, according to the Manulex database, www.manulex.org). Thus, the dictation task involved all word types that are likely to be encountered in French and allowed us to test children's ability to use both nonlexical and lexical spelling strategies. Children were required to listen to one (pseudo)word at a time through headphones and to subsequently write it down on a sheet. They could proceed to the next (pseudo)word at their own pace by pressing the spacebar. A word was considered as correct when it was spelled entirely correctly. Regarding the pseudowords, a word was considered correct as soon as its production was phonologically accurate (e.g. spelling verdulain or verdulein for verdulin). Raw scores (on 10 for the irregular words and on 20 for the regular and the pseudowords) were used for the analyses.

Children were tested individually in a quiet room at their school. At first grade, a first testing session included the serial order LTL (Hebb) task, the serial order STM task, and a paired-associate novel word learning task, the latter being reported elsewhere (see Ordonez Magro et al., 2018). One day later, we administered the item STM task and the receptive vocabulary task. At third grade, during a fist session, we again administered serial order STM and LTL tasks reported elsewhere (see Ordonez Magro et al., 2020), as well as the writing-to-dictation task that is the focus of this study. In a second session, children were tested with the item STM task, the receptive vocabulary task as well as with a word reading task reported in Ordonez Magro et al. (2020). Note that the first session always began with the LTL (Hebb repetition learning) task in order to minimize fatigue effects, and that the order of presentation of all other tasks was counterbalanced across participants. At both grades, Raven's colored progressive matrices were administered in a third session, in small groups of more or less six children. The same children were also tested at second grade, but these data are part of the study investigating the link between serial order memory and reading (Ordonez Magro et al., 2020).

Table 2.

Tasks administered at each point in time. The data collected in second grade is reported in Ordonez Magro et al. (2020).

1st grade	Session 1	▪ Serial order LTL task ▪ Serial order STM task ▪ Paired associate novel word learning task (reported in Ordonez Magro et al. (2018))
	Session 2	▪ Item STM task ▪ Receptive vocabulary task
	Session 3	▪ RCPM
2nd grade (this data is reported in Ordonez Magro et al. (2020))	Session 1	▪ Serial order LTL task ▪ Serial order STM task
	Session 2	▪ Item STM task ▪ Receptive vocabulary task ▪ Reading task
	Session 3	▪ RCPM
3rd grade	Session 1	▪ Serial order LTL task ▪ Serial order STM task ▪ Writing-to-dictation task
	Session 2	▪ Item STM task ▪ Receptive vocabulary task ▪ Reading task (reported in Ordonez Magro et al. (2020))
	Session 3	▪ RCPM

Statistical results are interpreted using the Bayes factor (BF), which reflects the likelihood ratio of two compared models. Here, the BF_{10} is used to determine the likelihood ratio of one model (containing some or all predictor variables) relative to the null model or relative to any other combination of predictor variables, and the BF_{01} is used to determine the reverse likelihood ratio (e.g., evidence for the null) (Kruschke, Aguinis, & Joo, 2012; van de Schoot et al., 2014; Wagenmakers, 2007). We relied on the guidelines proposed by Jeffreys (1961) for interpreting Bayes factors. A BF > 3 provides anecdotal evidence; a BF > 10 provides strong evidence, and a BF > 100 provides decisive evidence for the alternative hypothesis.

3. Results

Untransformed descriptive statistics for all tasks are shown in Table 3. Item STM tested at first grade and regular and pseudoword spelling tested at third grade were characterized by a negative skew. Square transformations were applied in order to normalize these measures (Field, 2005). Furthermore, as all variables have different maximum scores and ranges, we transformed all scores into z-scores (van Wingerden, Segers, van Balkom, & Verhoeven, 2018). In this study, we used a Bayesian approach for all statistical analyses (Dienes, 2011, 2016; Wagenmakers, 2007; Wagenmakers et al., 2008).

Table 3.

Descriptive statistics for all measures at first and third grade.

	Measures	M	SD	Skew[a]	Kurt[b]
1st grade	Age (months)	81.89	3.56	0.11	-1.03
	EVIP (/170)	89.46	13.11	-0.52	0.82
	RCPM (/36)	27.07	4.40	-0.58	-0.44
	item STM (/60)	44.09	8.23	-0.91	1.33
	serial order STM (mean score)*	.70	.07	0.07	-0.71
	filler (mean score)	.26	.12	0.40	-0.09
	Hebb (mean score)	.38	.24	0.63	-0.67
	filler (1st half)	.28	.15	-	-
	filler (2nd half)	.23	.14	-	-
	Hebb (1st half)	.33	.23	-	-
	Hebb (2nd half)	.43	.27	-	-
3rd grade	Age (months)	105.9	3.52	0.13	-1.01
	irregular word spelling (/10)	4.07	2.31	0.31	-0.42
	regular word spelling (/20)	15.65	2.95	-0.58	-0.55
	pseudoword spelling (/20)	17.19	2.52	-1.56	2.39

Note. Hebb scores reflect proportions of correct responses. EVIP = vocabulary knowledge measure; RCPM = Raven's colored progressive matrices.

[a] Standard error Skewness cutoff = + 0.22.

[b] Standard error Kurtosis cutoff = + 0.44.

*Note that this score is only available for 98 participants due to an encoding issue during data collection with 18 participants.

3.1 Preliminary analyses

To make sure that serial order learning occurred in the Hebb repetition task, we first analyzed our Hebb data by collapsing the trials of each sequence type into first- and second half scores (see also Archibald & Joanisse, 2013; Mosse & Jarrold, 2008; Ordonez Magro et al., 2018, 2020; Smalle et al., 2016, 2019). The data on trials 1 to 4 were collapsed into a first half score and the data on trials 6 to 9 were collapsed into a second half score. Serial order LTL was defined in terms of improvement from the first to the second half. Note that Hebb repetition learning reflects the transition from a temporary sequence to a more durable representation of this sequence, and hence reflects both STM and LTL processes (Szmalec et al., 2009). The first score representing performance averaged over the first half of the Hebb trials can be considered to rely more on STM than on long-term memory processes. The second score representing performance averaged over the second half of the Hebb trials can be considered to more strongly reflect LTL capacity. We ran a 2 (Sequence type: filler vs. Hebb) x 2 (Half: first vs. second) Bayesian repeated measures ANOVA. Based on Mosse and Jarrold (2008) as well as Archibald and Joanisse (2013), we compared performance on the first and second halves for each sequence type (Hebb and filler trials). Bayesian analyses were computed by using the JASP software package (Love et al., 2015). Results for the Hebb repetition task are plotted in Figure 1.

Results showed decisive evidence for an effect of Sequence type (BF_{10} = 1.58e^{+12}), with better recall performance for Hebb (.38±.24$_{SD}$) as compared to filler (.26±.12$_{SD}$) sequences. Anecdotal evidence against an effect of Half ($BF_{01} = 1/BF_{10}$, thus, $BF_{01} = 1/0.35 = 2.85$) was observed while there was decisive evidence for the presence of an interaction between Sequence type and Half (BF_{10} = 29,985). We observed higher scores on the second half (.43±.27$_{SD}$) than on the first half (.33±.23$_{SD}$) for Hebb, but not for filler sequences (.23±.14$_{SD}$ versus .28±.15$_{SD}$), which reflects the occurrence of Hebb repetition learning in our sample. Note that for children, a decrease of performance for filler sequences across halves is believed to be due to a fatigue effect (Archibald & Joanisse, 2013; Mosse & Jarrold, 2008).

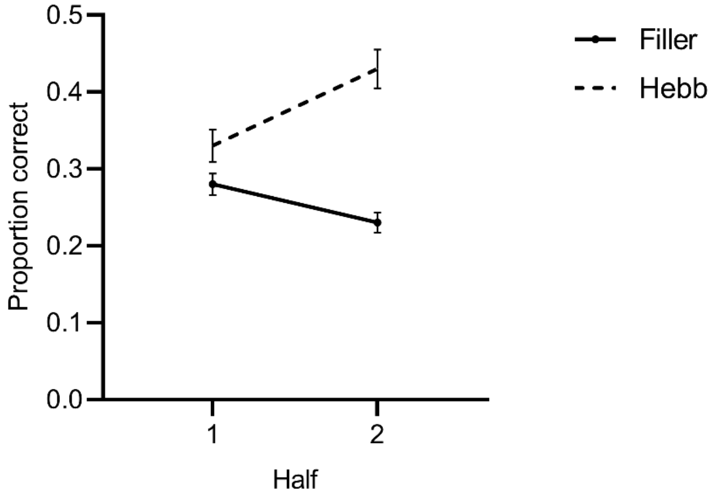

Figure 1. Mean proportion of items correctly recalled (with standard errors) at first grade for Hebb and filler sequences by sequence halves.

3.2 Bayesian regression analyses

We conducted Bayesian regression analyses in order to examine the involvement of serial order memory in spelling and the specific implication of serial order STM and LTL ability in writing of irregular, regular, and pseudowords. Regression analyses were also conducted by using the JASP software package (Love et al., 2015). Due to an encoding issue during the serial order STM task for 18 participants, the analyses including this variable were only run on 98 instead of 116 participants.

Regression analyses assessed the link between the different spelling measures and serial order STM/LTL, while controlling at the same time for the influence of nonverbal intelligence (RCPM) and vocabulary knowledge (EVIP), as these measures were correlated with most memory measures (see Table 4). We defined serial order LTL as recall performance on the second half of the Hebb trials, while controlling for recall performance on the second half of the corresponding filler trials, thereby controlling for STM baseline differences in the Hebb repetition paradigm (Bogaerts et al., 2016; Bogaerts et al., 2015; Mosse & Jarrold, 2008; Ordonez Magro et al., 2018; Smalle et al., 2017; Staels & Van den Broeck, 2015). More concretely, in order to control for STM baseline differences, we included the 2nd half of filler sequences in the model. We use the term “Hebb measure” to refer to the 2nd half of Hebb trials, and “filler measure” to refer to the 2nd half of filler trials.

A first set of analyses allowed us to determine the specificity of the associations between serial order STM/LTL and later spelling abilities. When assessing the association with the serial order STM measure, RCPM, EVIP, item STM, and serial order STM were entered in the model. When assessing the association with the Hebb (LTL) measure, RCPM, EVIP, filler, and Hebb measures were entered in the model. Additionally, the specific association of each form of serial order memory with spelling ability was assessed by entering both serial order STM and Hebb measures in the regression. To do so, RCPM, EVIP, serial order STM, and the Hebb measures were entered in the model.

Table 4.

Persons' correlation analyses between vocabulary knowledge (EVIP), nonverbal intelligence (RCPM), and memory measures tested at first grade. Correlations are flagged according to BF_{10}.

	EVIP	RCPM
Item STM	.33**	.23
Serial order STM	.41**	.22
2^{nd} filler	.20	.24*
2^{nd} Hebb	.17	.26*

Note. *$BF_{10} > 3$, ** $BF_{10} > 100$.

Bayesian regression analyses determined the model (combination of predictor variables) associated with the largest evidence given the data. The bigger the Bayes factor (BF_{10}), the stronger the evidence in favor of the corresponding model against the null model (Lee & Wagenmakers, 2013). We present the BF value of the model(s) associated with the strongest evidence and specific Bayesian effect values for each predictor variable ($BF_{forward}$ = comparison of the model with the effect against the null model; $BF_{backward}$ = comparison of the largest model with the effect against the same model that excludes the effect).

3.2.1 Dependent variable: irregular word spelling

When entering item and serial order STM measures into the regression model, the predictor variable of spelling acquisition associated with the highest BF_{10} value against the null model was the serial order STM measure ($BF_{10} = 224$). An analysis of specific effects confirmed that the serial order STM measure was the predictor associated with the largest evidence, whether compared only with the null model ($BF_{forward}$ = 224) or whether compared with all other predictor variables ($BF_{backward}$ = 148). The serial order STM measure explained 12% of specific variance of irregular word spelling.

When assessing the model containing the serial order LTL measures, the predictor variable associated with the highest BF_{10} value against the null model was the filler measure (BF_{10} = 2.67), which was directly followed by the Hebb measure (BF_{10} = 2.55), but the evidence for these effects was anecdotal.

When entering both serial order STM and LTL measures, the predictor variable associated with the highest BF_{10} value against the null model was the serial order STM measure (BF_{10} = 224), as confirmed by an analysis of specific effects ($BF_{forward}$ = 224; $BF_{backward}$ = 40). When compared to serial order LTL, the serial order STM measure explained 9% of specific variance in irregular word spelling.

3.2.2 Dependent variable: regular word spelling.

When running the same set of analyses for regular word spelling, we observed that the predictor variable with the strongest evidence was the item STM measure (BF_{10} = 32), which was confirmed by an analysis of specific effects ($BF_{forward}$ = 32; $BF_{backward}$ = 8). Item STM was directly followed by the serial order STM measure (BF_{10} = 6). The item STM measure explained 7% of specific variance in regular word spelling.

When assessing the prediction with the serial order LTL measure, the predictor variable associated with the strongest evidence was the Hebb measure (BF_{10} = 8). This was confirmed by an analysis of specific effects ($BF_{forward}$ = 8; $BF_{backward}$ = 3). The Hebb measure explained 5% of specific variance in regular word spelling.

When entering both serial order STM and LTL, the predictor variable associated with the highest BF_{10} value was the serial order STM measure (BF_{10} = 6), as confirmed by an analysis of specific effects ($BF_{forward}$ = 6; $BF_{backward}$ = 2). When compared to serial order LTL, serial order STM explained 3% of specific variance in regular word spelling scores.

3.2.3 Dependent variable: pseudoword spelling.

For the prediction of pseudoword spelling ability, the predictor variable with the highest BF_{10} value was the serial order STM measure (BF_{10} = 1,336). This was confirmed by an analysis of specific effects ($BF_{forward}$ = 1,336; $BF_{backward}$ = 403). The serial order STM measure explained 15% of specific variance in pseudoword spelling scores.

When entering the serial order LTL measures as predictor variables, the variable associated with the highest BF_{10} value was the filler measure (BF_{10} = 3), as confirmed by an analysis of specific effects ($BF_{forward}$ = 3; $BF_{backward}$ = 2), but the evidence for this effect was anecdotal.

When entering both serial order STM and LTL, the predictor variable associated with the highest BF_{10} value was the serial order STM measure (BF_{10} = 1,336), as confirmed by an analysis of specific effects ($BF_{forward}$ = 1,336; $BF_{backward}$ = 4,829). When compared to serial order LTL, the serial order STM measure explained 20% of specific variance in pseudoword spelling.

In sum, irregular and pseudoword spelling were best predicted by serial order STM, while regular word spelling was best predicted by item STM and similarly linked to serial order STM and LTL. See Figure 2 for a synthesis of results.

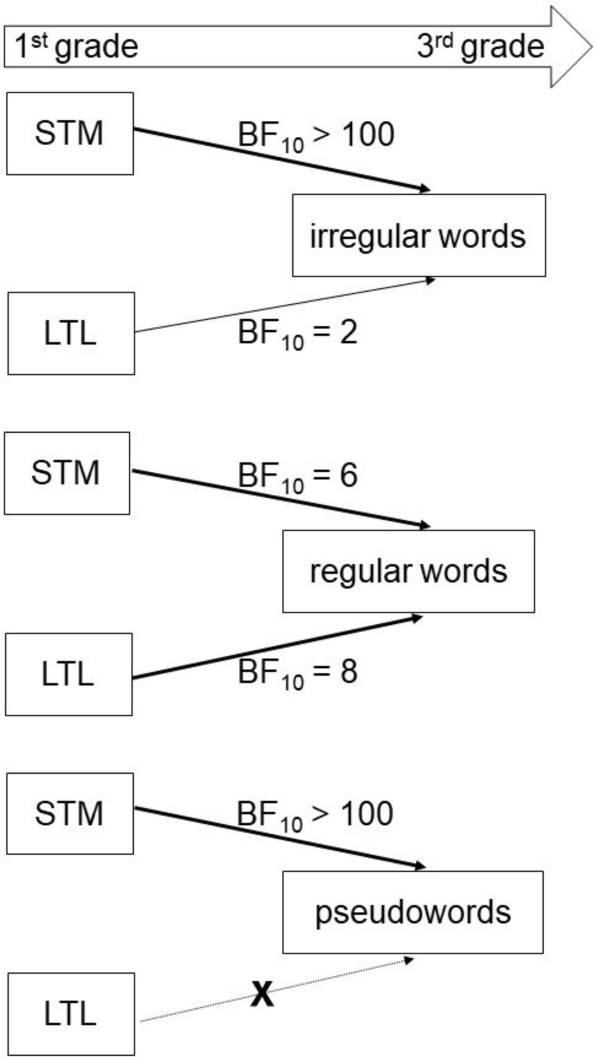

Figure 2. Illustration of predictions between serial order STM and LTL tested at first grade, and spelling measures tested at third grade. Arrows shown in bold denote the prediction with the highest BF_{10}. The dashed arrow and the "x" denote that there is no evidence for an association between LTL and pseudoword spelling.

4. Discussion

Although an important number of studies has allowed to elucidate the cognitive mechanisms underlying reading, the cognitive basis of spelling remains, to this day, less well understood. Recent findings have allowed to clarify the mechanisms involved in reading by showing the importance of the role of serial order STM and LTL in reading acquisition (Binamé & Poncelet, 2016a; Bogaerts et al., 2015, 2016; Hachmann et al., 2014; Holmes et al., 2008; Martinez Perez, Majerus, Mahot, et al., 2012;

Martinez Perez, Majerus, & Poncelet, 2012; Martinez Perez, Steve, et al., 2013; Romani et al., 2015; Szmalec et al., 2011). Although there exists nowadays evidence for a link between serial order memory and reading acquisition, the first empirical attempts at clarifying the involvement of serial order memory in spelling have been a long time coming. Moreover, note that it is still not clear whether the observed associations between serial order memory and reading/spelling acquisition in the literature are due to the fact that serial order memory ability supports written language acquisition or whether serial order memory is shaped by reading and/or spelling skills. To demonstrate that serial order memory subserves written language acquisition, one should measure memory abilities before reading/spelling acquisition. In their study, Martinez Perez, Majerus, and Poncelet, (2012) observed that serial order STM tested in kindergarten significantly predicted reading ability measured at first grade, supporting the assumption that serial order STM may be an important determinant of reading acquisition. On the other hand, there is also evidence for an inverse link, namely that serial order STM performance may be influenced by reading/spelling ability. In their study, Smalle et al. (2019) compared illiterate adults with matched literates and observed better serial order STM performance for the literate compared to the illiterate participants, while serial order LTL abilities were comparable across groups. This observation points toward an impact of reading acquisition on serial order STM but not LTL ability. These findings are in line with Demoulin and Kolinsky (2016) who argue that learning to read, due to its sequential nature, may to some extent train serial order STM ability. Thus, as far as we know, the evidence nowadays suggests a bidirectional link between serial order STM and written language acquisition, whereas the link between serial order LTL and written language needs further investigation.

In the present study, we brought together two lines of research, one focusing on short-term and the other one on long-term memory aspects of language development, in order to achieve a more complete understanding of how serial order STM and LTL interact during the acquisition of spelling abilities. To do so, we used memory tasks that were specifically developed to maximize the retention of serial order information and that allowed us to investigate the potential link between serial order

STM/LTL performance and spelling abilities. We hypothesized that spelling performance is determined by the ability to temporarily maintain the elements defining a written sequence in their correct order in STM, as well as the ability to consolidate this sequential arrangement in long-term memory. We assumed serial order STM to allow the temporarily maintenance of the constituent graphemes during phoneme-grapheme conversion, before writing down the word. Therefore, we expected serial order STM to particularly predict the spelling of novel words (operationalized via pseudowords), which primarily relies on phoneme-to-grapheme conversion mechanisms. Serial order LTL was rather expected to allow the creation of orthographic representations that lead to a more automatic spelling of irregular and regular words, via a more direct lexical spelling strategy.

As expected, we observed that pseudoword spelling was best predicted by serial order STM performance. Furthermore, regular word spelling was, as expected, predicted by serial order LTL ability but also similarly linked to serial order STM. Note however that regular word spelling was better predicted by item STM than by serial order memory. Finally, and rather unexpectedly, we observed that irregular word spelling was better predicted by serial order STM than by LTL.

The link between serial order STM and pseudoword reading converges with the idea that pseudowords do not dispose of any orthographic representations in long-term memory and therefore, that children need to spell these words by use of nonlexical, letter-by-letter decoding. This nonlexical spelling strategy requires to convert each phoneme into its corresponding grapheme. Subsequently, the constituent graphemes must be temporarily maintained in STM in their exact serial position until all phonemes have been converted. Finally, the speller has to assemble all graphemes in their correct serial order to produce the written word. This is where we assume serial order STM to play a crucial role, in order to avoid both order errors (like e.g., *wrom* instead of *worm*) as well as the erroneous production of anagrams (such as spelling *spot* instead of *stop*).

Regular word spelling was observed to be better predicted by item STM compared to serial order memory. Given that item information is known to involve access to long-term linguistic representations (Nairne & Kelley, 2004; Saint-Aubin & Poirier, 2005; Kowialiewski, Van Calster, Attout, Phillips, & Majerus, 2020), this link may represent the activation of phonological knowledge during the time-demanding spelling of regular words. We further also found that regular word spelling was similarly (although weakly) predicted by serial order STM and LTL. The expected link between serial order LTL and regular word spelling can be explained by the fact that regular words are generally introduced very early in the curriculum, through *decodable books* (Castles et al., 2018). Decodable books are texts consisting mainly of regular words that can be read correctly by the mere use of a nonlexical grapheme-to-phoneme decoding strategy, while unavoidably also containing a few irregular words such as *est* (*/ɛ/, s/he is* in English) and *fait* (*/fɛ/, s/he does* in English). These books allow children to read independently and by doing so, through practice, to gradually consolidate newly encountered orthographic representations in long-term memory (Share, 1995, 2004), presumably through Hebb repetition learning mechanisms (Bogaerts et al., 2015, 2016; Szmalec et al., 2011). Indeed, according to Share's *self-teaching hypothesis*, each decoding of a novel word provides children with the opportunity to acquire novel orthographic representations. Assuming that reading and spelling share the same orthographic lexicon, it can be expected that our third graders already disposed of long-term orthographic representations for several regular words that are frequently encountered in decodable books and that were used in our dictation task (e.g., *verbe* ["verb" in English] or *couleur* ["color" in English]). Thus, these representations could have been easily accessed during regular word spelling, presuming a predictive relationship between serial order LTL skills and regular word spelling, as we demonstrated in the present study. The link with serial order STM can be explained by the fact that unfamiliar regular words can easily be spelled by the use of a nonlexical spelling procedure, which is assumed to rely on serial order STM mechanisms (Romani et al., 1999). Thus, we hypothesize that our participants used a nonlexical spelling strategy for words or parts of words that were not yet familiar to them.

The unexpected observation that irregular word spelling was best predicted by serial order STM rather than by serial order LTL, is likely to be a consequence of the fact that third graders encounter irregular words less frequently than regular words (Castles, Rastle, & Nation, 2018). This hypothesis is also supported by our descriptive data (see Table 2) showing that only 40% of the irregular words were correctly spelled as compared to 78% of the regular words. We propose that the experience with irregular words was insufficient for the children to create long-term orthographic representations of these words. When an orthographic representation of a word is not well specified, the representation may be accessed only partially, as a consequence of which a nonlexical spelling strategy has to be appealed in order to decode the unknown part(s) of the word. This is in line with the *overlapping wave model* proposed by Kwong and Varnhagen (2005), according to which children dispose of a large repertoire of spelling strategies and select a strategy that requires the least amount of effort, but which is at the same time most likely to lead to a correct spelling. This account of our data also fits with Houghton and Zorzi's (2003) connectionist dual-route model, according to which the access to the nonlexical and the lexical route during spelling can occur in parallel and the combined output of both routes determines the final spelling. We therefore believe that the link between serial order STM and irregular word spelling probably reflects the use of a mainly nonlexical spelling strategy to process the irregular words (or subparts of these words) that are not yet specified in the orthographic lexicon. In this line of reasoning, we would expect an association between LTL and irregular word reading to emerge in a later stage of spelling development than third grade. Another reason for the involvement of serial order STM in irregular word spelling may be that irregular words are composed of particularly complex and rather rare phoneme-grapheme relationships. Decoding such complex words is likely to be time demanding, as the beginning speller has to identify, amongst several possibilities, how to spell the complex part of irregular words (e.g., in French /ɛ̃/ can be spelled "in", "ain", and "ein"). Spelling irregular words may therefore imply to maintain in STM the product of the already converted phonemes for a much longer duration compared to when decoding words with more typical sound-to-spelling correspondences. In other words, given the less systematic phoneme-grapheme relationships characterizing irregular words, analyzing each component and matching it to its corresponding and less predictable grapheme can be considered as an additional, time consuming demand. This is where we assume that serial order STM plays an important role in irregular word spelling, allowing the temporal maintenance of all graphemes in their correct serial position until each phoneme has been converted for production. This hypothesis is in line with Demoulin and Kolinsky (2016) who assume that dealing with irregular words, due to their complexity, engages serial order STM requirements in particular.

In sum, we showed that serial order STM was associated with the spelling of all word types in third graders. We believe that the orthography of all dictated words was not yet (well-)represented in third graders' long-term memory, leading to the use of a nonlexical spelling strategy involving serial order STM mechanisms to spell unfamiliar words. Moreover, we showed that regular word spelling was best predicted by item STM but also by serial order LTL. Regarding these findings, we propose that item STM may play a role in the temporary access of long-term sublexical representations during the spelling task. Moreover, we assume that serial order LTL mechanisms may support the creation of stable representations of frequently encountered regular words in the children's orthographic lexicon, presumably through Hebb repetition learning mechanisms.

As detailed in the Introduction part of this article, similar findings have been observed for reading acquisition (Binamé & Poncelet, 2016a; Bogaerts et al., 2016; Martinez Perez, Majerus, & Poncelet, 2012b; Nithart et al., 2011; Ordonez Magro et al., 2020), but also for vocabulary acquisition (Leclercq & Majerus, 2010; Majerus, Heiligenstein, Gautherot, Poncelet, & Van der Linden, 2009; Majerus, Poncelet, Elsen, & Van der Linden, 2006; Ordonez Magro et al., 2018; Smalle et al., 2016; Szmalec et al., 2009; Szmalec et al., 2012). Indeed, recent studies have shown that serial order STM is an important predictor of early stages of vocabulary acquisition. Learning a novel word essentially comes down to learning a particular sequence of phonemes. When asked to produce a novel word that is encountered for the first time, one has to encode each phoneme in STM and correctly assemble the sequence in its correct serial order allowing the oral production of the word. Serial order LTL has been shown to be implicated in later stages of vocabulary acquisition, when the initial sequence of phonemes becomes gradually consolidated, through repetition learning, as a unitary lexical representation in long-term memory. Thus, there is nowadays increasing evidence that the ability to temporarily maintain serial order information in STM and the ability to consolidate serial order information in long-term memory are important predictors of oral and written language acquisition, in typical as well as in atypical populations.

Finally, note that our results regarding spelling abilities are comparable to those observed in reading (see Ordonez Magro et al., 2020). In that study, we observed that reading as measured in second and third grade is especially linked to earlier serial order STM ability. Similar to spelling, regular word reading was also linked to serial order LTL. Thus, the findings observed in the present study are in accordance with our data observed in reading ability, which supports the assumption that reading and spelling depend on the acquisition of similar knowledge and that both are supported by common cognitive processes (Curtin et al., 2001; Holmes & Babauta, 2005; Juel, 1988; Purcell et al., 2017).

To conclude, note that we only used auditory memory tasks in the present study, which may raise the question of whether serial order memory and spelling are linked just because both tasks are verbal in nature or whether more specifically the memorization of serial order information supports spelling. Several recent studies have shown a link between serial order memory and (written and spoken) language acquisition for both verbal and visuo-spatial serial order memory. In their study, Mosse and Jarrold (2008) have observed that both verbal and a visuo-spatial Hebb repetition learning tasks predicted novel phonological word learning performance. Moreover, Martinez Perez et al. (2015), Bogaerts et al. (2016), as well as Hachmann et al. (2014) observed that serial order memory deficits can occur in both verbal and visuo-spatial modalities. Furthermore, the assumption of domain-general serial order processing abilities is also supported by neuroimaging studies showing that similar synaptic changes occur regardless of which type of stimuli need to be processed (Jensen & Lisman, 2005). In line with this, several researchers have proposed that serial order information is represented in the human memory system in a domain-general manner (Couture & Tremblay, 2006; Depoorter & Vandierendonck, 2009). Based on this, we would expect an association between spelling acquisition and both auditory and visual serial order STM and LTL tasks.

5. Conclusion

Based on recent evidence showing that serial order memory is an important contributor to reading development, we proposed to adopt a serial order memory account to elucidate the still poorly understood mechanisms that are involved in spelling abilities. In this study, we showed that serial order STM tested at first grade was associated with regular, irregular, and pseudoword spelling abilities tested two years later. Moreover, regular word spelling was to a comparable extent also predicted by serial order LTL. In the light of these findings, we propose that serial order STM is particularly involved in (subparts of) words for which the speller does not yet dispose of well-specified orthographic representations and which therefore require to use a nonlexical spelling strategy. On the other hand, we suggest that serial order LTL is implicated in the creation of long-term orthographic representations of novel words thanks to repeated exposure, which allows the use of a direct lexical strategy to spell known words (such as familiar regular words, as observed in the present study).

CRediT

Laura Ordonez Magro: Conceptualization, Method, Formal analysis, Investigation, Writing - Original Draft, Visualization **Steve Majerus:** Conceptualization, Method, Supervision, Funding acquisition **Lucie Attout:** Investigation, Supervision **Martine Poncelet:** Method **Eleonore Smalle:** Method **Arnaud Szmalec:** Conceptualization, Method, Supervision, Funding acquisition

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Appendix

Bayesian regression analyses for the spelling measures with the serial order STM and LTL measures as predictor variables.

Dependent variable: irregular word spelling

Table A1 Bayesian regression analysis for the irregular word spelling measure with the STM measures as predictor variables: analysis of effects

Predictors	**$BF_{Inclusion}$**	**$BF_{Backward}$**	**$BF_{Forward}$**
RCPM	0.25	0.33	0.27
EVIP	0.32	0.40	0.30
Item STM	0.29	0.36	0.33
Serial order STM	204.83	148.47	224.68

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Table A2 Bayesian regression analysis for the irregular word spelling measure with the LTL measures as predictor variables: analysis of effects

Predictors	**$BF_{Inclusion}$**	**$BF_{Backward}$**	**$BF_{Forward}$**
RCPM	0.29	0.36	0.25
EVIP	0.52	0.54	0.63
2^{nd} half filler	1.46	1.09	2.67
2^{nd} half Hebb	1.41	1.12	2.55

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Table A3 Bayesian regression analysis for the irregular word spelling measure with the STM and LTL measures as predictor variables: analysis of effects

Predictors	**$BF_{Inclusion}$**	**$BF_{Backward}$**	**$BF_{Forward}$**
RCPM	0.26	0.33	0.27
EVIP	0.25	0.42	0.30
Serial order STM	98.19	40.11	224.68
2^{nd} half Hebb	0.34	0.43	1.89

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Dependent variable: regular word spelling

Table A4 Bayesian regression analysis for the regular word spelling measure with the STM measures as predictor variables: analysis of effects

Predictors	$BF_{Inclusion}$	$BF_{Backward}$	$BF_{Forward}$
RCPM	0.29	0.34	0.24
EVIP	0.46	0.68	0.24
Item STM	8.73	8.19	32.61
Serial order STM	1.26	1.85	6.74

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Table A5 Bayesian regression analysis for the regular word spelling measure with the LTL measures as predictor variables: analysis of effects

Predictors	$BF_{Inclusion}$	$BF_{Backward}$	$BF_{Forward}$
RCPM	0.28	0.37	0.23
EVIP	0.29	0.36	0.27
2nd half filler	0.52	0.57	1.00
2nd half Hebb	5.91	3.94	8.30

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Table A6 Bayesian regression analysis for the regular word spelling measure with the STM and LTL measures as predictor variables: analysis of effects

Predictors	$BF_{Inclusion}$	$BF_{Backward}$	$BF_{Forward}$
RCPM	0.30	0.36	0.24
EVIP	0.35	0.44	0.24
Serial order STM	3.16	2.39	6.74
2nd half Hebb	1.00	0.89	2.85

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Dependent variable: pseudoword spelling

Table A7 Bayesian regression analysis for the pseudoword spelling measure with the STM measures as predictor variables: analysis of effects

Predictors	$BF_{Inclusion}$	$BF_{Backward}$	$BF_{Forward}$
RCPM	0.37	0.42	0.21
EVIP	0.62	0.81	0.24
Item STM	0.53	0.87	4.73
Serial order STM	432.14	403.73	1,336.46

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Table A8 Bayesian regression analysis for the pseudoword spelling measure with the LTL measures as predictor variables: analysis of effects

Predictors	**$BF_{Inclusion}$**	**$BF_{Backward}$**	**$BF_{Forward}$**
RCPM	0.32	0.47	0.19
EVIP	0.32	0.41	0.30
2nd half filler	3.10	2.84	3.09
2nd half Hebb	0.34	0.40	0.36

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.

Table A9 Bayesian regression analysis for the pseudoword spelling measure with the STM and LTL measures as predictor variables: analysis of effects

Predictors	**$BF_{Inclusion}$**	**$BF_{Backward}$**	**$BF_{Forward}$**
RCPM	0.34	0.35	0.21
EVIP	0.53	0.56	0.24
Serial order STM	2,193.01	4,829	1,336.46
2nd half Hebb	0.59	0.66	0.24

Note. >3=anecdotal evidence for a link; >10=strong evidence for a link; >100=decisive evidence for a link.