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Children's knowledge of single- and multiple-letter grapheme-phoneme correspondences: An exploratory study

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ABSTRACT

In this study, we examined Australian children's knowledge of single- and multiple-letter grapheme-phoneme correspondences (GPCs), and the influence of five different factors – GPC complexity, phoneme status, the child's name, GPC entropy, and GPC frequency – on GPC knowledge. Data from 337 Australian children enrolled in Kindergarten to Grade 3 were included in the study and analyses were performed using mixed effects models. Results indicate that GPC knowledge varied across children and GPCs, children were almost twice as likely to accurately pronounce single-letter graphemes compared to multiple-letter graphemes, and performance was better for GPCs which occur more frequently in text. GPCs with higher entropy values (less consistent) had close to 40% lower odds of being known by children. The study has practical implications by providing an evidence-based guide for the order in which GPCs should be introduced to children in schools.

1. Introduction

Learning the names of letters (letter-name knowledge) and the sounds that letters represent in written text (letter-sound knowledge) are two important skills for learning to read an alphabetic script. Letter-name knowledge in kindergarten is a strong predictor of early reading skills (Bond & Dykstra, 1997; Leppänen, Aunola, Niemi, & Nurmi, 2008; Scarborought, 1998; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004; Torppa, Lyytinen, Erskine, Eklund, & Lyytinen, 2010), because it appears to assist children's development of letter-sound knowledge (for a review, see Foulin, 2005). Letter-sound knowledge, in turn, enables children to phonologically decode written words that they have not yet learned (Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Share, 1999, 2008).

At least two factors have been suggested to play a role in children's development of letter-name knowledge: a child's name and the phonological structure of letter names. Research has shown that children learn the names of letters (and how to write letters) in their own name earlier than other letters, because they have a particular interest in learning to write their own name and are exposed to the written form of their name more often than other written words (containing other letters; Bloodgood, 1999; Justice, Pence, Bowles, & Wiggins, 2006; Treiman & Broderick, 1998). Children also appear to learn the names of letters more easily when those names have a consonant + vowel (CV) structure (e.g., /b/ + /iː/ for the letter B; Treiman & Broderick, 1998; Treiman, Tincoff, & Richmond-Welty, 1997), however, at least one study has not found this result (McBride-Chang, 1999).

While it is not yet clear if the phonological structure of letter names plays a critical role in letter-name knowledge, the research overwhelmingly supports that the phonological structure of letter names has a role in letter-sound knowledge (e.g., Evans, Bell, Shaw, Moretti, & Page, 2006; Justice et al., 2006; McBride-Chang, 1999; Treiman, Tincoff, Rodriguez, Mouzaki, & Francis, 1998; Treiman,

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Weatherston, & Berch, 1994). This has been explained in terms of the *iconicity* of letters; that is, most letter names contain the sound that the letter represents (Treiman & Kessler, 2003). For example, children find it easier to learn the sounds for letters with names that contain the corresponding sound (e.g., T is pronounced /ti:/ which contains the sound /t/) than for letters that do not (e.g., Y is pronounced /waI/ like the word WHY, which does not contain the sound /j/; Treiman et al., 1998). Further, children find it easier to learn the sounds for letters that have a CV name structure than a VC name structure (Treiman et al., 1998). That is, letter sounds are easier to learn for letters like B and K, where the letter sound is at the beginning of the letter name (i.e., /bi:/ and /keI/, respectively) than letters like F and M where the sounds is at the end of the letter name (e.g., /ɛf/ and /ɛm/, respectively). Several other factors have been shown to affect the development of letter-sound knowledge including the method of literacy instruction (Piasta & Wagner, 2010), the visual similarity of letters (e.g., b and d) and similarity of sounds (e.g., /m/ and /n/; Carnine, 1976, 1980), and the consistency (or ambiguity) of letter sounds (e.g., D is pronounced /d/ versus C pronounced /k/ or /s/; Huang, Tortorelli, & Invernizzi, 2014; Treiman, 1993; Treiman et al., 1998).

Of these various factors, it is the phonological structure of letter names that has received the most attention in the literature. However, the English writing system is complex and children need to learn many other spelling units than the 26 letters, or *graphemes*, of the alphabet and their associated sounds, or *phonemes*. In particular, children must learn many grapheme-phoneme correspondences (GPCs) where more than one letter corresponds to a single sound such as EA-/i:/ as in HEAT and SH-/ʃ/ as in SHIP. However, the phonological structure of letter names cannot account for how children learn these multiple-letter GPCs, since these graphemes (i.e., EA, SH) are compounds of single letters (or *graphs*) and therefore do not have names *per se*. Single-letter GPCs may be useful for children's early reading development and allow children to read simple one-syllable words, however, many words contain multiple-letter GPCs that children must learn in order to become skilled readers who master complex words and texts. It is therefore important to understand what factors are associated with children's knowledge of single-letter and multiple-letter GPCs. However, surprisingly few studies have focused on multiple-letter GPCs, and even fewer have investigated factors associated with children's knowledge of single- and multiple-letter GPCs in the same study.

To address this gap in the literature, we explored the association of several factors (see below) with children's knowledge of both single- and multiple-letter GPCs. Based on previous research, we selected five factors that could be applied to both single- and multiple-letter GPCs: (1) GPC complexity (i.e., single- or multiple-letter grapheme), (2) phoneme status (i.e., consonant or vowel phoneme), (3) the child's own name (i.e., own-name advantage), (4) GPC entropy (i.e., measure of consistency), and (5) GPC frequency. Below we provide a review of the literature for each of the five factors in order to explain our predictions for the current study.

1.1. GPC complexity

In English, there is a mismatch between the number of speech sounds (phonemes) and the number of letters in the alphabet. There are many more phonemes (approximately 44 depending on the accent) than there are letters, but the concatenation of letters (e.g., C and H to CH) compensates for this (Venezky, 1999). A distinction between GPCs can thus be made in terms of the complexity of the grapheme, that is, whether a grapheme consists of a single letter (e.g., P, E) or multiple letters (e.g., PH, EA). Single- and multiple-letter GPCs differ in (at least) one important way. As the name implies, a multiple-letter GPC contains at least two letters that each map onto a phoneme (or phonemes). This may interfere with learning the phoneme associated with the grapheme. For example, learning the OI-/ɔI/ association, as in COIN, may be hampered by knowledge of the O-/ɒ/ and I-/I/ associations as in HOT and HIT, respectively. Indeed, research with adults has shown that when presented with a multiple-letter grapheme, the phonemes associated with the individual letters of the multiple-letter grapheme are activated (Peereman, Brand, & Rey, 2006). Moreover, we have observed that children in the Macquarie Univeristy Reading Clinic often respond with two successive phonemes for multiple-letter graphemes, for example, saying /ɒ/ and then /œ/ for OA, and this pattern has also been reported in acquired dyslexia (e.g., /ʌ/ and /I/ for UI when reading the word SUIT; Newcombe & Marshall, 1985). Research with children does indeed suggest that multiple-letter GPCs are more difficult than single-letter GPCs irrespective of whether the GPC is a consonant or vowel (Frederiksen & Kroll, 1976; Marinus & de Jong, 2008; Olson, Forsberg, Wise, & Rack, 1994). While this may be the case, it is important to note that literacy instruction programs often (if not always) teach single-letter GPCs before multiple-letter GPCs, which means that there may be an order-of-teaching confound. Nonetheless, we predict based on previous research that children in the present study will find multiple-letter GPCs more difficult than single-letter GPCs and thus provide fewer correct target responses to multiple-letter than single-letter GPCs.

1.2. Phoneme status

A distinction can be made in terms of whether a GPC is a consonant or vowel. Several studies have demonstrated that a GPC's phoneme status (as consonant or vowel) influences children's GPC knowledge. For example, Stuart and Coltheart (1988) found that young children were less likely to know vowels than consonants when asked to provide the sound associated with each of the letters of the alphabet. A further analysis of children's errors showed that incorrect responses tended to be letter names, which for vowels are often referred to as the "long vowel sound" (e.g., A pronounced /eI/ as in BABY). It was argued that the relatively poorer performance for vowels was not due to the (low) consistency of vowels relative to consonants (i.e., generally, vowel letters have more possible pronunciations than consonant letters) as children also made letter name responses for consonants. However, responding with /eI/ to the letter A and /bi:/ to the letter B is different, because A does make the /eI/-sound in words (e.g., BABY, TABLE), while B does not make the /bi:/-sound in words (it makes the /b/-sound as in BAG). Graham (1980) assessed primary-school students' knowledge of vowel and consonant single- and multiple-letter GPCs using an extensive nonword reading task and also found that children struggled more with vowels than consonants. Finally, a more recent study shows that children have more difficulty with multiple-letter GPCs for vowels than consonants in nonword reading (Gilbert, Compton, & Kearns, 2011). Based on this research, we predict that the children in the present study will have more difficulty with vowels relative to consonants.

1.3. Own-name advantage

Children have been found to be better able to learn those letters of the alphabet that occur in their own name (Justice et al., 2006; Treiman & Broderick, 1998; Villaume & Wilson, 1989). Whether the own-name advantage extends to children's GPC knowledge is less clear. For example, Treiman and Broderick (1998) found that 4- and 5-year-olds were no more likely to know the phoneme associated with a single-letter grapheme if the grapheme was in the child's name, even if the grapheme was the initial of their name. However, a more recent study by Huang et al. (2014) did find evidence in support of the own-name advantage as children in their study were more likely to know the phoneme associated with individually presented graphemes, if the grapheme occurred as the initial of the child's first name. Why did Huang et al. (2014) find own-name advantage for GPC knowledge, when Treiman and Broderick (1998) did not? One possibility relates to how the initial grapheme of children's names was categorised. Huang et al. (2014) "made distinctions between child names in which the letter represents its most common sound [i.e., the target sound] and when it does not". When asked to provide the phoneme for the grapheme C, children named Cathy or Carl would be expected to show an own-name advantage, whereas Celine or Charlie would not, and this is what was found. Treiman and Broderick (1998) did include this important distinction (in Study 2 only), but they did not find a significant own-name advantage for GPC knowledge when this was assessed using either a free choice task (similar to Huang et al.; i.e., what sound does this letter make?) or a two-choice task (e.g., is this a /də/ or a /pə/?). This could be in part due to Treiman and Broderick's small sample size (n = 47; Huang et al.: n = 1197), restricted number of (single-letter) graphemes (n = 6) or as the authors suggest, because of a confound in the design. Namely, half of the consonants included have names with a VC structure (i.e., M, R, and S), whereas the other half have names with a CV structure (i.e., D, J, and K) and the children in their study performed significantly better on graphemes with a CV than VC name structure. This effect may have distorted the own-name advantage as it was not factored into the own-name analyses.

But what about multiple-letter GPCs and the own-name advantage – is Charlie more likely to know the CH-/tʃ/ association than Chris, Cathy, or Danielle? The only study that we are aware of reporting on this (Huang et al., 2014) did not find evidence to support an own-name advantage on knowledge of multiple-letter GPCs. In the present study, we wish to further explore this issue. Specifically, we include (1) single- and multiple-letter GPCs, (2) a more extensive list of both vowel and consonant multiple-letter GPCs (e.g., AI for Aidan, PH for Phillip), and (3) we use the name distinction similar to Huang et al. (2014). Given the mixed research findings and relative lack of research on the own-name advantage on knowledge of GPCs and in particular multiple-letter GPCs, we do not have any predictions regarding own-name advantage.

1.4. GPC entropy

English is often described as a deep orthography, which means that the relationship between orthographic and corresponding phonological units is not one-to-one. Some *graphemes* can represent more than one phoneme (orthography to phonology in reading; e.g., TH as in THIS versus THIN, OO as in NOOK versus NOON) and some *phonemes* can be represented by different graphemes (phonology to orthography in spelling; e.g., /i:/: SEA and SEE; /ɛə/: STARE and STAIR). Of interest in this study is the translation from orthography to phonology; consequently, we refer specifically to GPC consistency (referred to as ambiguity in Huang et al., 2014). The consistency of a GPC is defined as the relative frequency of that GPC (e.g., EA-/i:/) as a proportion of all occurrences of that grapheme (i.e., EA). Previous research has shown that GPC consistency affects children's GPC knowledge with inconsistent GPCs being more difficult for children to learn. This is the case both when GPC knowledge is assessed using a standard GPC task (i.e., the child sees a grapheme and is asked to provide the associated phoneme) and a nonword reading task (Huang et al., 2014; Siegel & Faux, 1989).

While previous studies have used a dichotomous measure of GPC consistency (i.e., consistent versus inconsistent), we suggest that this is a rather crude measure that does not adequately reflect the nuances of GPC consistency. Instead, we use a more sophisticated and sensitive measure, GPC entropy, which takes into account both the number of different pronunciations associated with a grapheme and the relative proportions of these pronunciations (see Section 2 and Table 1 for details of how entropy values are calculated and example calculations). While entropy values for GPCs have been calculated for several different orthographies (Borgwaldt, Hellwig, & de Groot, 2004; Protopapas & Vlahou, 2009), we are not aware of any other studies that have investigated the effect of GPC entropy (as an index of GPC consistency/ambiguity) on children's GPC knowledge. We predict that children in the present study will show more difficulty with more inconsistent GPCs, that is, those with higher entropy values.

1.5. GPC frequency

The frequency with which children encounter their own name has been suggested as a possible explanation for the own-name advantage. However, there is another frequency index which might be important for children's development of GPC knowledge; namely, the frequency with which GPCs occur in text. Previous research has shown that children may implicitly learn about GPCs in spelling (e.g., D is pronounced /d/ versus C pronounced /k/ or /s/ Gingras & Sénéchal, 2019; Treiman & Kessler, 2011) and the graphotactic and morphological patterns in spelling (Deacon, Conrad, & Pacton, 2008). Such implicit statistical learning has also been found for developing readers in terms of GPC acquisition, where vowel GPC frequency and the consonantal context of vowels is predictive of GPC knowledge (Steacy et al., 2019; Treiman, Kessler, & Bick, 2003; Treiman, Kessler, Zevin, Bick, & Davis, 2006). While these studies have focused specifically on the pronunciation of a limited set of vowel GPCs during nonword reading, if the observed frequency effect generalizes for vowel and consonant GPCs more broadly, then children should find it easier to learn and therefore know a greater proportion of more frequent GPCs compared to the proportion of less frequent GPCs. If children do not make use of the written frequency of GPCs, then we would not expect to find a difference in knowledge across GPCs with different frequencies.

Several studies have investigated the effect of frequency on GPC knowledge for vowels and consonants; however, critically, these studies have used a measure of grapheme frequency (and not GPC frequency). That is, how often a particular grapheme occurs in written text. We believe it is important to differentiate between the two frequency indices as they measure something quite different, especially when a grapheme has multiple possible pronunciations (e.g., A has at least three different pronunciations; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). While the results of previous studies are mixed in terms of the effect of grapheme frequency on GPC knowledge (Ecalle, 2004; Evans et al., 2006; Huang et al., 2014; Treiman, Levin, & Kessler, 2012), we suggest that GPC frequency might be a more appropriate index for predicting children's GPC knowledge and hence, we include this measure in the present study. We predict that children will have better knowledge of GPCs that occur more frequently in text than GPCs that occur less frequently.

In summary, the current study investigated children's knowledge of the mappings between letters and sounds, GPCs. GPC knowledge is crucial for children's reading development and it is therefore important to understand what factors influence this knowledge. As far as we are aware, this is the first study to investigate children's GPC knowledge using a comprehensive list of both single- and multiple-letter GPCs. More specifically, we explore how five factors – GPC complexity (single- or multiple-letter grapheme), phoneme status (consonant or vowel), a child's own name (own-name advantage), GPC entropy (an index of consistency), and GPC frequency (frequency in written text) – are associated with children's knowledge of single- and multiple-letter GPCs.

Table 1
Example entropy calculations as indices of grapheme-phoneme correspondence consistency.

Grapheme		Phoneme	Example	Number of occurrences (token frequency)	Probability (token consistency)	Entropy components
B	→	/b/	BIN	509843	1	0.00
Entropy value: H(B) = 0.00						
EA	→	/eI/	STEAK	13340	0.1027	−0.337249396
	→	/Iə/	HEAR	5085	0.0392	−0.183035783
	→	/eə/	PEAR	366	0.0028	−0.023873174
	→	/ε/	BREAKFAST	35564	0.2738	−0.511698234
	→	/i:/	PEACH	75514	0.5815	−0.454844119
Entropy value: H(EA) = 1.511						

Table 2
Study sample demographics by grade (class), group and age.

Grade level	N	Group		Age (years)	
		Boys	Girls	Range	Mean (SD)
Kindergarten	82	39	43	5.45–6.72	6.06 (0.33)
Grade 1	87	34	53	6.45–7. 79	7.13 (0.30)
Grade 2	75	34	41	7.36–8.77	8.14 (0.32)
Grade 3	93	53	40	8.43–9.85	9.18 (0.33)

Table 3
Single- and multiple-letter graphemes used in the LeST (ordered from highest to lowest written frequency).

Index card														
1	t	n	s	i	l	r	a	d	c	p	e	m	o	b
2	er	g	f	u	v	k	h	j	w	y	ar	z	th	sh
3	ng	ch	ee	x	qu	oo	ph	oi	ai	kn	ay	oa	oy	au
4	wr	ea	gn	aw	ir	wh	ou	ur	igh					

Note. LeST = Letter-sound Test.

2. Method

The Macquarie University Human Ethics Committee approved the methods of this research. Children participated in the study with parental consent. Verbal assent was also obtained from each child at the beginning of the testing session.

2.1. Participants

We analysed data from a total of 337 children (177 girls, 160 boys) enrolled in Kindergarten, Grade 1, Grade 2, and Grade 3 who participated in the study. Children ranged in age from 5 years 5 months to 9 years 10 months. See Table 2 for sample demographics.

Children were recruited from two independent co-educational schools in the Sydney metropolitan area. Both schools were selected on the basis that they performed within the average range for Australia on the National Assessment Program – Literacy and Numeracy (NAPLAN), and were in areas that were in the average range on two socio-economic status (SES) measures (Australian Bureau of Statistics, 2006). The schools were typical of Australian schools in that they taught reading using a combination of different methods. One school used a mix of phonics and sight words. Phonics instruction was focused on teaching grapheme-phoneme associations where the pronunciation is the most common (e.g., A pronounced /æ/ as in HAT and CH is pronounced /tʃ/ as in CHECK) and sight words were to be memorised via frequent exposure (i.e., word recognition). This school did not use a particular reading instruction program, but rather used a mix of several programs. The other school predominately used the THRASS method (Davies & Ritchie, 2003). THRASS is a comprehensive teaching method which covers handwriting, reading and spelling. The THRASS method has a strong focus on phonemic awareness (i.e., segmenting words into sounds), and teaches children the 44 phonemes in English and how these may be represented in writing (e.g., the phoneme /f/ can be spelled F as in FIONA, FF as in COFFEE, or PH as in PHONE). Children also learn a word example for each of the sound spelling associations (e.g., BIRD for B, RABBIT for BB), in addition to learning frequently occurring other words (e.g., THE, SAID, YOU). Teachers use a THRASS chart with the 44 phonemes, divided into a consonant and a vowel section, with the most common spellings (graphemes) for each phoneme shown with a word and a picture example. If a phoneme has other less common spellings (e.g., PB for /b/ as in CUPBOARD) these are represented with an asterisk on the chart. Less common spellings are called Grapheme Catch-Alls (GCAs) and are used to teach frequently occurring words that do not have a common spelling pattern (e.g., SAID where the /ε/-sound is spelled with AI). The THRASS method does not have a prescribed teaching sequence for phoneme grapheme associations and teachers can teach these associations in the order they wish (e.g., to match their other resources), and words are introduced as they become useful for children (i.e., depends entirely on the individual child and class room). While the THRASS method teaches sound-to-spelling associations (phoneme-to-grapheme) and not spelling-to-sound associations (grapheme-to-phoneme), research suggests that neither approach is superior, at least during beginning literacy instruction (Callinan & van der Zee, 2010). In the present study, we explored whether there were any difference across schools given that the approaches to literacy instruction varied between the schools, but we did not find this to be the case (see Analytic Approach below).

2.2. Procedure

Children were tested individually on the Letter-Sound Test (LeST; Larsen, Kohnen, Nickels, & McArthur, 2015) in a quiet room of their school in the final term of the academic year (in Australia the academic year has four terms and the final term runs from October to December). The LeST, which took 5–10 min to administer, was administered as part of a battery of reading and spelling tests which formed a large norming study. The test battery was administered in a fixed order to all students (Marinus, Kohnen, & McArthur, 2013; McArthur et al., 2013).

2.3. Measures

2.3.1. GPC knowledge

Children's knowledge of single- and multiple-letter GPCs was assessed using a single task (no parallel forms), namely, the LeST (Larsen et al., 2015). The LeST comprises 51 items presented on A4 index cards (9–14 items per card) in Arial 24-point font. See Table 3 for a full list of the GPCs included in the LeST. Children were shown the first of the index cards and asked to provide the sound that each of the single- or multiple-letter GPCs makes. The scoring procedure for the LeST is similar to previous studies in that only the most common phoneme associated with a grapheme is accepted – for single-letter vowel GPCs the short vowel sound was accepted, the hard sound for C and G (i.e., /k/ and /g/, respectively) and /ks/

for X.[1] We refer to this as the *target responses* or *target phonemes*. The LeST has high test-retest reliability (ICC = 0.88) and moderate to strong criterion validity (Pearson's *r* between 0.49 and 0.70) with the nonword list from the Castles and Coltheart 2 (CC2; Castles et al., 2009) and a 39-item nonwords list (experimental nonwords varying in length and complexity). Internal consistency of the LeST in the present study was good ($r_{KR\text{-}20}$ = 0.88). For a full description of the LeST including how the test was constructed (e.g., item selection), normative data, and further information regarding reliability and validity, see Larsen et al. (2015).

For the present study, GPCs included in the LeST were coded in terms of complexity, phoneme status, entropy and frequency. Below we outline the classifications used and an overview of the coding of each of the GPCs is presented in Appendix A.

2.3.2. GPC complexity

GPCs were classified according to whether the grapheme contained a single letter and coded 0 or contained multiple letters and coded 1. There was an equal number (25) of single-letter and multiple-letter GPCs.

2.3.3. Phoneme status

GPCs were coded 0 if they were consonants and 1 if they were vowels. There were 29 consonant GPCs and 21 vowel GPCs.

2.3.4. Own-name advantage

To code the data for the own-name advantage analysis, we checked if the pronunciation of the initial grapheme of a child's first name corresponded to a target response on the LeST. If this was the case it was coded 1, otherwise it was coded 0. For example, Charlie was coded 1 as CH is pronounced /tʃ/ and Cathy was coded 1 as C is pronounced /k/ (i.e., both are target responses on the LeST), but Charlotte and Celine were coded 0 as CH and C is pronounced /ʃ/ and /s/, respectively (i.e., neither are target responses on the LeST). First names were scored independently by the first author and a second scorer (a native English speaker) and agreement was high (94%). Any discrepancies were resolved through discussion. A total of 86.9% of children had a first name that began with a target phoneme.

2.3.5. GPC entropy

It is possible to calculate entropy using either type frequency (i.e., number of different word types in which a GPC occurs) or token frequency (i.e., the total number of times all of the words, in which a GPC appears, occur in a written corpus) counts, but following the recommendations of Balota, Yap, and Cortese (2006) and Protopapas and Vlahou (2009), we used token frequency measures in this study. More specifically, the entropy (*H*) value for each GPC on the LeST was calculated as the negative sum, over the alternative mappings, of the products of each probability times its logarithm:

$$H = -\sum_{i=1}^{n} p_i \log_2 p_i$$

GPCs with an entropy value of zero have a perfect one-to-one mapping (i.e., consistent correspondence) between grapheme and phoneme (e.g., B-/b/). However, as entropy increases, the consistency of the GPC decreases. For example, the grapheme EA has five possible phoneme mappings of which /iː/ (as in TEA) is the most frequent. Overall, the grapheme EA occurs 129,869 times and on 75,514 occurrences it is pronounced /iː/, amounting to a probability (**p**) of 0.1027 for the mapping EA to /iː/. The probabilities for the other mappings are 0.1027 for /eI/, 0.092 for /Iə/, 0.0028 for /eə/, and 0.2738 for /ε/, respectively (see Table 1). By inserting these probabilities into the entropy formula, we get the entropy value H(EA) = 1.1511, describing the (in)consistency of the pronunciation of the grapheme EA.

2.3.6. GPC frequency

The frequency measure used in the present study refers to the frequency of GPCs rather than graphemes as discussed above. That is, how often a particular GPC occurs in written text. GPC frequency counts are generated from the empirical investigations of large word corpora and there have been several such investigations (e.g., Coltheart et al., 2001; Fry, 2004; Hanna, Hanna, Hodges, & Rudorf, 1966). In the present study, we used the frequency counts by Coltheart et al. (2001), which are based on the monosyllabic words (over 7500 different words) from the widely used CELEX database[2] (Baayen, Piepenbrock, & Gulikers, 1995). In their look-up table, Coltheart and colleagues provide both type and token frequency counts. We chose to use Coltheart and colleagues' frequency counts as it allowed us to explore if GPC type and token frequencies are differently associated with children's knowledge of GPCs.

2.4. Analytic approach

All analyses were performed using the R software environment for statistical computing and graphics (R Core Team, 2017). The lme4 package (Bates, Maechler, & Bolker, 2012) was used to perform generalized linear mixed models (GLMM) analyses. We employed a two-step approach. In the first step, we estimated a number of decreasingly complex models incorporating only the intercept as a fixed effect and, successively, random effects for students, items, classes, and schools. The purpose was to determine the appropriate random effects structure and differences between models were assessed using likelihood ratio tests. In the second step, we estimated the random effects structure determined in Step One and included fixed effects for GPC complexity, phoneme status, GPC entropy, GPC frequency and the interaction term between phoneme status and GPC entropy. We then added fixed effects for own-name and age,[3] before estimating a model adding the interaction term between own-name and age. Finally, we explored a complex interaction model in which we included fixed effects for GPC complexity, phoneme status, GPC entropy, and GPC frequency, and the interaction terms between GPC complexity, phoneme status, GPC entropy, GPC frequency and age, respectively.

3. Results

Descriptive data (see Fig. 1) shows that accuracy – the ability to provide the target phoneme for single or multiple-letter graphemes – varied across items and children. More than 80% of children correctly produced the target phoneme for 23 out of 50 items. Dividing the sample into younger and older children by a median split, we found that more than 80% of younger children correctly produced

[1] There was one exception to the scoring procedure. For TH both the voiced (e.g., THIS) and unvoiced (e.g., THANK) pronunciations were accepted. For this reason, TH was excluded from all analyses.

[2] CELEX is based on dictionary data from the Oxford Advanced Learner's Dictionary (1974, 41,000 entries) and the Longman Dictionary of Contemporary English (1978, 53,000 entries), and text corpus data from the COBUILD/Birmingham corpus (17.9 million words), which has been specifically used to develop CELEX frequency measures. While the CELEX frequencies are based on text samples from adult texts, evidence suggests that the distribution of GPCs in adult and children's books is similar (Solity & Vousden, 2009).

[3] Thank you to two anonymous reviewers for suggesting the inclusion of Age as a predictor.

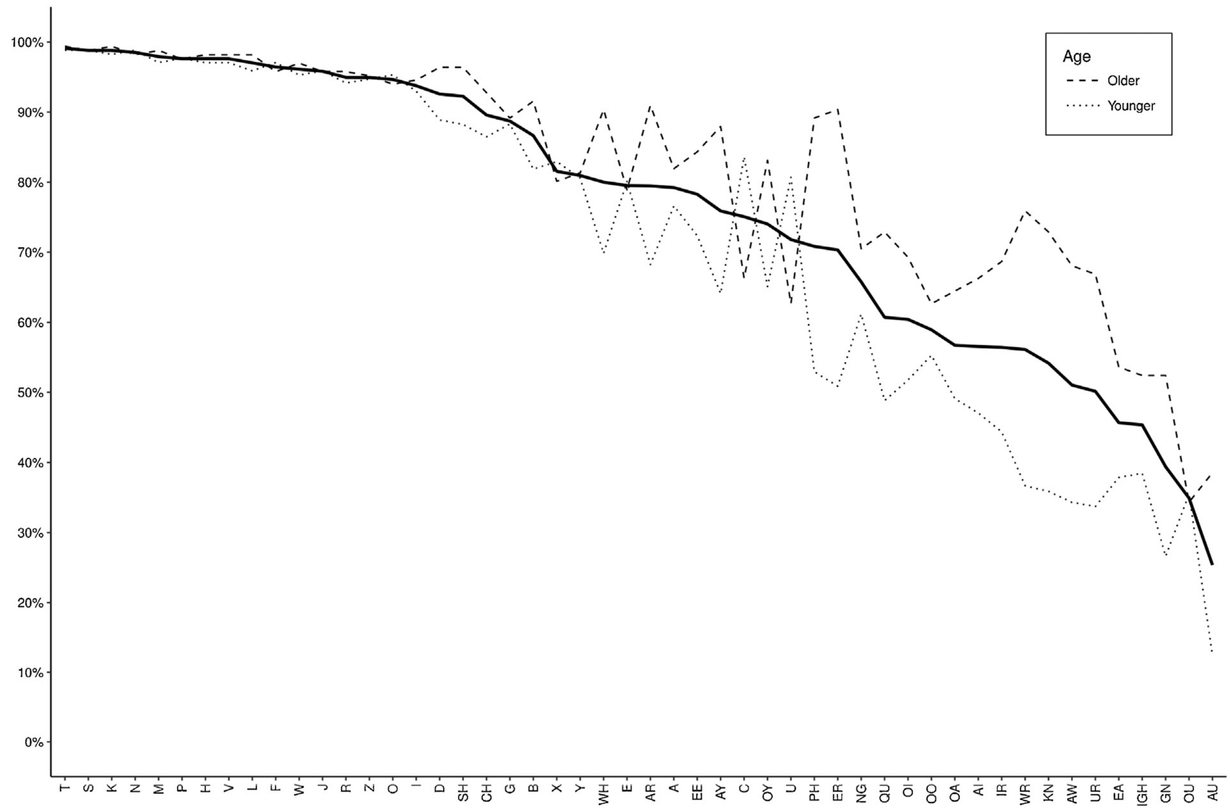

Fig. 1. Percentage of younger and older children producing the target response (phoneme) for each grapheme (the solid line represents the total sample of children). Items presented in order of decreasing accuracy.

Table 4
Modeling random effects for students, items (GPCs), classes, and schools. The null models were not significantly different and thus, the random effect for schools was excluded when modeling fixed effects.

	Null model 1			Null model 2		
	OR	CI	*p*	OR	CI	*p*
Fixed effects						
(Intercept)	7.39	3.99–13.70	<0.001	7.39	3.98–13.70	<0.001
	Variance		ICC	Variance		ICC
Random effects						
Students	0.858		0.110	0.858		0.110
Items	3.075		0.395	3.075		0.395
Classes	0.557		0.072	0.557		0.072
Schools	0.000		0.000			

Note. OR = Odds Ratio; CI = Confidence Interval; ICC = Intra Class Correlation.

the target phoneme for 25 out of 50 items. This was 30 out of 50 items for older children (see Appendix B).

As expected, children produced single-letter GPCs (e.g., P-/p/, 98%) more accurately, but two multiple-letter GPCs were also fairly accurate (i.e., SH-/ʃ/, 92%; CH-/tʃ/, 89%). As predicted, children in general were less accurate on vowels than consonants, and in particular multiple-letter vowel GPCs. Only two single-letter vowel GPCs were produced accurately by more than 80% of children (i.e., I-/I/ and O-/ɒ/) and only one multiple-letter vowel GPC (i.e., EE-/iː/) was known by more than 75% of children. The items that children had the most difficulty with were GN-/n/ as in GNOME (39% correct), OU-/aʊ/ as in SOUND (35%), and AU-/ɔː/ as in AUTOMATIC (25%).

Results from the mixed effects model analyses are presented in Tables 4 and 5. In the first step, we performed a preliminary multilevel analysis of null models with four levels (i.e., students, items, classes, and schools) and three levels (i.e., students, items, and classes), respectively (see Table 4). In the first model, the random effect of school explained zero variance. Excluding the random effect for school in the second model did not significantly reduce the fit of the model and we therefore collapsed the data across schools for subsequent analyses.

In the second step, we explored the effect of GPC complexity, phoneme status, GPC entropy, GPC frequency (token and type), own-name, and age on children's GPC knowledge (see Table 5). Results are reported as odds ratios (OR), where a significant OR greater (or less) than 1 indicates a positive (or negative) association with the predictor and an OR of 1 indicates no association with the predictor. For example, an OR of 1.35 indicates a 35% increase in the odds of correctly producing the target phoneme associated with a one unit increase in the predictor while controlling for all other variables. An OR of 0.65 indicates a 35% decrease in the odds. In Model 1 we included GPC complexity, phoneme status, GPC entropy and GPC frequency (token). The results indicated that all predictors were statistically significant in the model, which was in accord with our predictions. Children were less likely to produce the target phoneme for multiple-letter graphemes (OR = 0.17), vowels (OR = 0.45), and GPCs that had higher entropy values (i.e., less consistent; OR = 0.56). Further, more frequent GPCs were almost twice as likely to be accurately pronounced compared to less frequent GPCs (OR = 1.81).

In Model 2 we ran the same analysis, but token frequency was replaced with type frequency to further explore if these two indices of GPC frequency differentially predicted children's GPC knowledge. This was not the case: more frequent GPCs (using type frequency) still had 78% higher odds of being accurately pronounced compared to less frequent GPCs (OR = 1.78). GPC complexity and GPC entropy were still significant predictors with only very minor changes to the odds ratios (i.e., complexity: OR = 0.16

Table 5
Results from linear mixed effects models analyses.

	Null model		Model 1: item level predictors		Model 2: item level predictors		Model 3: item level predictors		Model 4: person level predictors		Model 5: person level predictors	
	OR	*p*	OR	*p*	OR	*p*	OR	*p*	OR	*p*	OR	*p*
Fixed effects												
(Intercept)	7.39	<0.001	30.98	<0.001	29.75	<0.001	29.32	<0.001	29.25	<0.001	29.52	<0.001
Grapheme complexity			0.17	**<0.001**	0.16	**<0.001**	0.17	**<0.001**	0.17	**<0.001**	0.17	**<0.001**
Phoneme status			0.45	**0.013**	0.56	0.079	0.52	0.090	0.52	0.091	0.52	0.091
GPC entropy[a]			0.56	**0.045**	0.54	**0.034**	0.70	0.433	0.70	0.432	0.70	0.431
GPC frequency (token)[b]			1.81	**<0.001**			1.85	**<0.001**	1.84	**<0.001**	1.84	**<0.001**
GPC frequency (type)[b]					1.78	**0.001**						
Phoneme status × GPC entropy							0.69	0.515	0.69	0.510	0.69	0.511
Own-name									1.54	0.134	1.26	0.402
Age (in months)[b]									1.46	**0.042**	1.47	**0.038**
Age × Own name											0.39	**<0.001**
Random effects												
Students	0.914		0.914		0.914		0.914		0.915		0.918	
Items	3.150		0.789		0.820		0.783		0.780		0.785	
Classes	0.526		0.496		0.497		0.496		0.198		0.199	
Explained variance (percentage) in relation to the null model												
Students		0.00		0.00		0.00		−0.11		−0.44		
Items		74.95		73.97		75.14		75.24		75.08		
Classes		5.70		5.51		5.70		62.36		62.17		

Note. GPC = Grapheme-phoneme correspondence; OR = Odds Ratio. Bold values indicate significant effects.
[a] Index of consistency using token count.
[b] Log-scaled.

and entropy: OR = 0.54). However, while the odds ratio for phoneme status remained almost the same, the associated *p*-value indicated that it was no longer a significant predictor in the model (OR = 0.56). This result may be due to a lack of statistical power based on the (relatively small) sample size (as discussed in the Section 4.1, below).

In Model 3 we included the phoneme status by GPC entropy interaction term to (tentatively) explore whether GPC entropy acts differently across vowels and consonants, and help understand why children seem to be less accurate on vowels compared to consonants. However, neither the interaction nor phoneme status nor GPC entropy were significant in the model.

In Models 4 and 5 we added fixed effects for own-name and age, and the own-name by age interaction term, respectively. In Model 4 we found that age, but not own-name, was a significant predictor in the model (age: OR = 1.46 and own-name: OR = 1.54). GPC complexity and token frequency remained significant in the model, while phoneme status, GPC entropy, and the phoneme type by GPC entropy interaction remained non-significant. In Model 5 we found a significant own-name by age interaction effect (OR = 0.39), indicating that older children benefitted less from the own-name advantage. Finally, in Model 6 (identical to Model 1, but with the inclusion of higher order interaction terms between GPC complexity, phoneme status, GPC entropy, and GPC frequency, and age, respectively), we found that GPC complexity, phoneme status, GPC entropy, and GPC frequency were significant predictors in the model with only minor changes to odds ratios compared to the other models. We also found significant interaction effects, except for age by phoneme status. For example, the largest odds ratio was for the age by GPC complexity interaction (OR = 2.51, $p < 0.001$), indicating that older children were two and a half times more likely to know complex GPCs. However, we interpret these results with caution as Model 6 failed to converge (see Appendix C for model results).

When comparing the overall fit of the models (fit indices Model 1: AIC = 12,846 and BIC = 12,908; Model 2: AIC = 12,848 and BIC = 12,909; Model 3: AIC = 12,848 and BIC = 12,917; Model 4: AIC = 12,846 and BIC = 12,931; Model 5: AIC = 12,835 and BIC = 12,928), we did not find a significant difference between models and, as can be seen, fit indices are very similar. About 75% of the variance at the item (GPC) level was accounted for across the five fitted models.

4. Discussion

Learning the sounds that letters represent is a crucial skill for children's reading development in an alphabetic language. It is therefore important to understand how this skill develops and what factors are associated with it. The purpose of this research was to investigate children's knowledge of single- and multiple-letter GPCs, and the association between GPC knowledge and five different factors, namely: (1) GPC complexity (i.e., single- or multiple-letter grapheme), (2) phoneme status (i.e., consonant or vowel phoneme), (3) the child's own name (initial GPC in first name), (4) GPC entropy (i.e., measure of consistency), and (5) GPC frequency.

From our descriptive analysis, it was evident that there was variation in children's knowledge of GPCs, both across children and across GPCs. The majority (more than 80%) of younger children correctly provided the target phoneme for half of the graphemes, while older children unsurprisingly were better and provided the target phoneme for 30 out of 50 graphemes. Further and as predicted, children performed better on single-letter GPCs, with the exception of two multiple-letter consonant GPCs (i.e., SH-/ʃ/ and CH-/tʃ/). A possible explanation as to why children performed so well on these two items is that both are highly consistent (low entropy values) and occur frequently in written text (see Appendix A for entropy and frequency values). This may also account for why PH-/f/ (i.e., PH as in PHONE) was relatively more difficult, as, while consistent, it is less frequent.

From the descriptive statistics children also appeared to exhibit greater difficulty with vowels and in particular multiple-letter vowel GPCs compared to consonants, although this finding may not be as robust as phoneme status (consonant or vowel GPC) was not a significant predictor across the five models where the other predictors are controlled for. Only two single-letter vowel GPCs were known by more than 80% of children and only one multiple-letter vowel GPC was known by more than 75% of children.

It is interesting to note that A-/æ/ (as in CAP) was not among the easiest vowels, even though it is generally recommended that children be introduced to this vowel very early in teaching (e.g., Jolly Phonics; Lloyd, 1992, Letters and Sounds; Primary National Strategy, 2007). Instead, I-/I/ as in PIT and O-/ɒ/ as in POT were the vowels on which accuracy was the highest. If easier letter sounds should be taught before harder letter sounds, our data suggests that I-/I/ and O-/ɒ/ should be taught first, followed by E-/ɛ/, A-/æ/, and finally U-/ʌ/. However, our findings contrast with Huang et al. (2014), who found A-/æ/ to be the easiest vowel, followed by O-/ɒ/, E-/ɛ/, I-/I/, and U-/ʌ/. While we do not have a clear explanation for the contrasting results, it is possible that the easily distinguishable letter-form of O may have affected the acquisition of the O-/ɒ/ association and hence, making this item easier for children in our study. Another possibility is the difference in English accent, with the present study using Australian-English and Huang et al. (2014) used American-English. Thus, orthographic features of graphemes and different accents affecting vowels may play a role in children's letter sound acquisition.

For multiple-letter vowel GPCs, two were particularly difficult for children, namely, OU-/aʊ/ as in SOUND and AU-/ɔ:/ as in AUTOMATIC. Only 35% and 25% of children provided the target phoneme for these, respectively. Many teachers use the rule "when two vowels go walking the first does the talking" to teach multiple-letter vowel GPCs. What this means is that in the word BOAT the O says its name /əʊ/ and the A is *silent*. While this rule is useful for some multiple-letter vowel GPCs (e.g., OA as in BOAT, EA as in TEA, and IE as in PIE), this is not helpful for learning OU-/aʊ/ or AU-/ɔ:/. It may be confusing for children to learn this rule that applies *sometimes* and may hamper learning of some multiple-letter GPCs.

We now turn to the results from the mixed effects models and the factors associated with children's GPC knowledge. First, we looked at GPC complexity, which is concerned with whether the grapheme consists of a single letter (e.g., P, E) or multiple letters (e.g., PH, EA). GPC complexity was a significant predictor in all our models. Single-letter graphemes had around an 83% higher odds of being accurately pronounced compared to multiple-letter graphemes (e.g., Model 1: OR = 0.17). This is in line with our prediction and adds further support to previous research (Frederiksen & Kroll, 1976; Marinus & de Jong, 2008; Olson et al., 1994). It is not surprising that multiple-letter GPCs should be more difficult for children and a possible explanation is that multiple-letter GPCs contain two (or more) single letters that each map onto their own associated phoneme or phonemes. This may cause interference or inhibit access to the phoneme with which the multiple-letter grapheme is associated. Another possible explanation is related to the age at which children are taught different GPCs. When children first begin receiving literacy instruction they are most often (if not always) taught single-letter GPCs before being taught multiple-letter GPCs that allow them to read more complex text. While children in the present study were sampled from schools that use a mixed approach to literacy instruction and hence, minimised the possible confound of type of literacy instruction, it is possible that our results could be confounded by age of acquisition effects. That is, that children had been introduced to and taught single-letter GPCs at an earlier age and only later on had been taught multiple-letter GPCs. Tentative evidence from Model 6 lends indirect support for this as the GPC complexity by age interaction was found to be significant.

Second, we found evidence to suggest that children may find vowels more difficult than consonants. In fact, for every one vowel a child knew, they knew two consonants. However, the effect of phoneme status (i.e., consonant or vowel) on GPC knowledge was only statistically supported in Model 1, despite the odds ratio (and associated confidence interval) being stable across models. This indicates that the effect of phoneme status may lack robustness. Nonetheless, considering the results of the descriptive data and results from the mixed effects models, we cautiously suggest that our results are in accord with our prediction and previous research (Gilbert et al., 2011; Graham, 1980; Stuart & Coltheart, 1988). Also, to our knowledge, this is the first time that the degree of difficulty of vowels relative to consonants has been quantified using both single- and multiple-letter GPCs of which 29 were consonants and 21 were vowels.

We might then ask, what it is that make vowels GPCs more difficult than consonants GPCs for children? Undoubtedly, the acquisition of vowel GPCs is particularly interesting and complex as the name of vowel letters (e.g., name of E is /i:/) is also the sound which these letters and other multiple-letter units are used to represent (i.e., E-/i:/ as in ME, EE-/i:/ as in TREE, and EA-/i:/ as in TEA). Further, there are phonetic similarities between vowel sounds (e.g., /ɛ/-/I/, /æ/-/ɛ/) and there are many more vowel sounds than there are letters in the alphabet to represent these. It seems unlikely that the difficulty with vowels should be related to speech sound acquisition, as vowels are acquired *earlier* than consonants in language development (Priester, Post, & Goorhuis-Brouwer, 2011) and vowels present less difficulty for speech interpretation and intelligibility than do consonants (e.g., Cole, Yan, Mak, Fanty, & Bailey, 1996; Fogerty & Humes, 2012). Further, we note that the acquisition order of vowel GPCs in the present study does not fit clearly with the acquisition order of vowel phonemes in speech (McLeod, 2009). We are not aware of any studies that have used speech sound acquisition order to predict GPC knowledge. However, one study has focused on consonant speech sound acquisition and letter naming of consonants (Justice et al., 2006). This study found that children were better able to name letters that corresponded to consonant speech sounds acquired earlier rather than later in development.[4]

Returning to vowels, evidence from neuropsychological single-case studies of dysgraphia, aphasia and dyslexia does suggest that (phonologically and orthographically) consonants and vowels are distinct categorical representations (Khentov-Kraus & Friedmann, 2018; Miceli, Capasso, Benvegnù, & Caramazza, 2004). In particular, the study by Khentov-Kraus and Friedmann (2018) is relevant for our study as it reports 23 single cases of vowel letter dyslexia (i.e., selective impairment in reading vowels in words and nonwords). While this may lend support to the possibility that there is something special about vowels that make these more difficult for children there could be a more straightforward explanation. Namely, the spoken similarity of vowels (i.e., there is much greater spoken similarity between vowels than there is among consonants). The more limited discriminability between vowels may result in less distinct memories for vowels, which in turn could leave more room for error during vowel GPC acquisition. Taken together, there may be a complex interaction of several factors when learning vowel GPCs, and more direct studies are required to better understand this.

Third, we investigated the own-name advantage, which states that children should be more likely to know those letters that occur in their name. In this study, we were specifically interested in whether children showed an advantage for the initial grapheme (single- or multiple-letter) of their name when asked to provide its associated phoneme. To our knowledge, only one study has explored the own-name advantage on (a limited set of) knowledge of multiple-letter GPCs in a preliminary analysis. In the present study, we included a comprehensive list of both single- and multiple-letter GPCs. In line with Huang et al. (2014) and Treiman and Broderick (1998), our results do not support the own-name advantage. For example, a child named Charlie was no more likely to know the CH-/tʃ/ association than a child whose name was Chris, Cathy or Danielle. Despite the lack of a significant effect of own-name on GPC knowledge, we did find a significant interaction with age, with older children benefitting less from the own-name advantage than younger children. It is possible that the own-name advantage could be similar to a (specific) frequency effect (i.e., frequency of own name), which washes out over time, possibly with increased exposure to text. That is, older children are exposed to many more words than just their name, whereas younger children are exposed to fewer words overall, thus increasing the impact of seeing their name.

Fourth, in the present study, we used a relatively sophisticated measure to index consistency, namely entropy, which takes into account all the phoneme mappings for a given grapheme and their relative proportion (e.g., Protopapas & Vlahou, 2009). We found that GPC entropy was a significant predictor of children's GPC knowledge. This is in line with our prediction and provides stronger (more conclusive) evidence for the effect of consistency on children's GPC knowledge compared to previous studies that have used *coarser* measures of GPC consistency (Huang et al., 2014; Siegel & Faux, 1989). This result has practical implications for classroom teachers when planning literacy instruction – specifically GPC instruction – as it suggests that GPCs with lower entropy values (i.e., that are less ambiguous) should be introduced before GPCs with higher entropy values (more ambiguous). To do this, teachers may find the GPC entropy values listed in Appendix A a useful resource.

Finally, this study found, as hypothesized, that GPC frequency was a significant predictor of children's GPC knowledge. Children had around an 80% higher odds of knowing more frequent GPCs relative to less frequent GPCs. GPC knowledge was not differentially predicted by the number of word types a particular GPC occurs in (type frequency) compared to the sum of the frequency of those word types (token frequency). As far as we are aware, the present study is the first to use GPC frequency (rather than letter (or grapheme) frequency) and investigate if type and token frequency have differential effects on GPC knowledge.

4.1. Limitations

The present study has a number of limitations which future studies may wish to address. One is that the sample was collapsed across four different grades in order to increase the sample size (and hence, statistical power) when performing the mixed effects analyses. We acknowledge that our sample size of more than 330 children may seem relatively small compared to some other studies investigating GPC (or letter-name) knowledge (Huang et al., 2014; Justice et al., 2006; Phillips, Piasta, Anthony, Lonigan, & Francis, 2012). Nonetheless, given that this is the first study to investigate children's knowledge of a comprehensive list of single- and multiple-letter GPCs and factors associated with children's GPC knowledge, it represents a solid starting point.

[4] In a supplementary analysis, we explored whether the consonant-order advantage extended to letter sounding, but we did not find evidence of this.

A second limitation relates to the fact that children who participated in the present study were drawn from only two schools. It could be argued that, for example, the literacy instruction or method used at each school may have influenced the results. However, both schools were typical of Australian schools and used a combination of phonics and sight words (whole words) to teach reading. One of the schools used the THRASS method predominately. Critically, however, the main findings of the study were robust even when effects of school on accuracy and interactions between school and grapheme complexity, phoneme status, GPC entropy, GPC frequency, and own-name, respectively, were explored in supplementary analyses. Nevertheless, we suggest that future studies would benefit from using a larger sample of children drawn form a wider variety of schools.

We encourage future studies to use GPC (rather than letter or grapheme) frequency (type and token) and GPC entropy as an index of consistency, and to investigate speech sound acquisition order or the orthographic structure of letters/graphemes and how this relates to children's GPC acquisition. Other child-related factors may also be included such as language background and specific measures of children's speech or oral language. Finally, we strongly encourage future studies to explore literacy instruction practices within schools and their relationship with children's GPC acquisition.

4.2. Implications for instruction

Letter-sound (GPC) knowledge directly influences children's reading development by allowing children to phonologically decode words they have not yet learned (Share, 1999). While children need to learn both single- and multiple-letter GPCs to become proficient readers, many studies to date have only focused on children's knowledge of single-letter GPCs. The present study is the first to explore children's knowledge of a comprehensive list of single- and multiple-letter GPCs and several factors associated with children's GPC knowledge. It therefore has direct implications for literacy instruction. First, the study provides new information regarding the sequence of acquisition of a comprehensive list of GPCs that includes both single- and multiple-letter GPCs, and consonants and vowels. As it seems natural to introduce children to easier GPCs before more difficult GPCs, Fig. 1 (earlier) can be used to guide the order in which teachers and literacy instructors introduce GPCs to beginning readers. As suggested earlier, it seems that the order in which many literacy instruction programs introduce single-letter GPCs does not correspond with what the current research shows about the acquisition order of GPCs. Second, the acquisition order of GPCs is also helpful for teachers as a guide for how much time should be devoted to teaching different GPCs and the amount of repetition for different GPCs. That is, the introduction of earlier acquired GPCs (i.e., easier GPCs) may progress quicker than the introduction of later acquired GPCs (i.e., harder GPCs), and easier GPCs may also require less time dedicated to repetition than harder GPCs.

Third, the present study provides new information regarding why some GPCs are easy for children to acquire and why some are harder to acquire. For example, we found that children struggled the most with GN-/n/ (as in GNOME), OU-/aʊ/ (as in SOUND), and AU-/ɔ:/ (as in AUTOMATIC). The two last items are both multiple-letter vowel GPCs that have relatively low consistency and frequency. In other words, these two items have multiple characteristics that make GPCs harder for children to learn. It is noteworthy that GN-/n/ – also a multiple-letter consonant low in frequency – was surprisingly difficult for children. Why could this be? One possibility is the low frequency alone. However, another possibly is that it has to do with the word position specifics of the item. That is, GN most often appears in word final position (e.g., SIGN, ALIGN) and only rarely in word initial or medial position (e.g., GNOME, POIGNANT). While we did not investigate word position in the present study, it is possible that this could somehow have negatively influenced performance on the LeST where test items were presented in isolation (and in a sense in word initial position).

In conclusion, the present study extends previous research on children's GPC knowledge by investigating a comprehensive set of both single- and multiple-letter GPCs in the same study. Our findings suggest that children's GPC knowledge is associated with GPC complexity (i.e., single- versus multiple-letter grapheme), phoneme status (i.e., consonant or vowel), GPC entropy, and GPC frequency. Further, the effect of a child's own name (initial grapheme) on GPC knowledge is stronger for younger than older children. The present study provides new insight into the order in which single- and multiple-letter GPCs should be introduced to children during beginning literacy instruction where the aim is generally to introduce easier GPCs before more difficult GPCs.

5. Declaration of interest

None.

Acknowledgments

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Appendix A

GPC	GPC complexity	Phoneme status	GPC entropy	Type frequency	Token frequency
t-/t/	0	0	0.000	1641	2081414
n-/n/	0	0	0.000	1169	1836402
s-/s/	0	0	1.285	2411	918372
i-/ɪ/	0	1	0.578	818	1359101
l-/l/	0	0	0.000	1639	562756
r-/r/	0	0	0.000	1364	443701
a-/æ/	0	1	1.636	729	1329249
d-/d/	0	0	0.340	1334	1232701
c-/k/	0	0	0.735	724	213457
p-/p/	0	0	0.000	1277	315754
e-/ɛ/	0	1	1.068	506	396199
m-/m/	0	0	0.000	833	746321
o-/ɒ/	0	1	1.605	483	901467
b-/b/	0	0	0.000	794	508525
er-/ʌr/	1	1	0.061	58	80649
g-/g/	0	0	0.986	513	165363
f-/f/	0	0	0.999	629	523968
u-/ʌ/	0	1	0.801	620	283584
v-/v/	0	0	0.000	286	155171
k-/k/	0	0	0.000	637	257224
h-/h/	0	0	0.000	307	740592
j-/ʤ/	0	0	0.003	122	42149
w-/w/	0	0	0.000	396	641173
y-/j/	0	0	0.969	67	77988
ar-/a:/	1	1	0.622	134	63256
z-/z/	0	0	0.128	83	6507
sh-/ʃ/	1	0	0.000	293	137319

ng-/ŋ/	1	0	0.786	59	49583
ch-/tʃ/	1	0	0.327	296	169611
ee-/i:/	1	1	0.002	194	169656
x-/ks/	0	0	0.000	60	21244
qu-/kw/	1	0	0.000	111	14532
oo-/u:/	1	1	1.142	137	56366
ph-/f/	1	0	0.000	29	4307
oi-/ɔI/	1	1	0.000	44	14108
ai-/eI/	1	1	0.995	119	33900
kn-/n/	1	0	0.000	40	37724
ay-/eI/	1	1	0.000	57	95589
oa-/əʊ/	1	1	0.288	91	15205
oy-/ɔI/	1	1	0.000	14	8053
au-/ɔ:/	1	1	0.535	56	7295
wr-/r/	1	0	0.000	43	10073
ea-/Iə/	1	1	1.511	189	76804
gn-/n/	1	0	0.000	26	3568
aw-/ɔ:/	1	1	0.000	102	17051
ir-/ʌr/	1	1	0.004	75	40128
wh-/w/	1	0	0.280	76	190827
au-/aʊ/	1	1	0.952	101	82304
ur-/ʌr/	1	1	0.000	73	11988
igh-/aI/	1	1	0.000	40	55873

Note: GPC = grapheme-phoneme correspondence. GPC complexity: single-letter grapheme = 0 and multiple-letter grapheme = 1. Phoneme status: consonant = 0 and vowel = 1.

Appendix B. GPC accuracy (%) ordered by decreasing accuracy

Item	Total sample	Younger children	Older children
T	99	99	99;1
S	99	99	99
K	99	98	99
N	99	99	98
M	98	97	99
H	98	97	98
P	98	98	98
V	98	97	98
L	97	96	98
W	96	95	97
F	96	97	96
J	96	96	96
R	95	94	96
Z	95	95	95
O	95	95	94
I	94	93	95
D	93	89	96
SH	92	88	96
CH	90	86	93
G	89	88	89
B	87	82	92
X	82	83	80
Y	81	81	81
WH	80	70	90
E	80	80	79
AR	79	68	91
A	79	77	82
EE	78	72	84
AY	76	64	88
C	75	84	66
OY	74	65	83
U	72	81	63
PH	71	53	89
ER	70	51	90
NG	66	61	70
QU	61	49	73
OI	60	52	69
OO	59	55	63
AI	57	47	66
OA	57	49	64
WR	56	37	76
IR	56	44	69
KN	54	36	73
AW	51	34	68
UR	50	34	67
EA	46	38	54
IGH	45	38	52
GN	39	27	52
OU	35	36	34
AU	25	12	39

Appendix C. Results from supplementary age interaction analysis (model failed to converge)

	Model 6	
	OR	*p*
Fixed effects		
(Intercept)	28.72	**<0.001**
Age (in months)[b]	0.96	0.0843
Grapheme complexity	0.21	**<0.001**
Phoneme status	0.43	**0.011**
GPC entropy[a]	0.55	**0.046**
GPC frequency (token)[b]	1.91	**<0.001**
Age × Grapheme complexity	2.51	**<0.001**
Age × Phoneme status	0.92	0.120
Age × GPC entropy	0.77	**<0.001**
Age × GPC frequency (token)	1.18	**<0.001**
Random effects		
Students	0.99	
Items	0.83	
Classes	0.22	

Note. GPC = Grapheme-phoneme correspondence; OR = Odds Ratio. Bold values indicate significant effects.

[a]Index of consistency using token count.

[b]Log-scaled.

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