Journal of Research in Reading
UKLA
The United Kingdom Literacy Association

Journal of Research in Reading, ISSN 0141-0423 *DOI:10.1111/1467-9817.12327*
Volume 00, Issue 00, 2020, pp 1–20

Complex phonological tasks predict reading in 7 to 11 years of age typically developing Russian children

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Background: The important role of phonological processing for reading has been demonstrated by many studies. The purpose of this research was to investigate the role of phonological processing for reading in Russian. Specifically, we tested whether the overall complexity of a phonological task predicts reading fluency and reading comprehension.
Method: We used seven phonological tests ranked according to the number of linguistic processes involved in each task. We examined the relative difficulty of the tests and the relationship between phonological processing and reading skills (reading fluency and comprehension of simpler and more difficult texts) in 90 typically developing 7 to 11 years-of-age Russian-speaking children.

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Results: Phonological tests that involved more linguistic processes had lower response accuracies. At the individual level, a greater estimated cost of adding a linguistic process to a phonological test was associated with a reliable decrease in reading fluency but not reading comprehension.
Conclusions: Our findings confirmed the substantial role of phonological processing in reading acquisition while stressing a higher predictive value of more complex phonological tests for reading fluency. The relationship between phonological processing and reading comprehension, in Russian, needs further investigations.

Keywords: reading comprehension, reading fluency, Russian language, phonological complexity, phonological processing

Highlights

What is already known about this topic

- Phonological processing contributes to reading in English and other languages using the Latin script.
- The results from tests addressing different aspects of phonological processing are highly intercorrelated, but some tests predict reading skills better than others.

What this paper adds

- Reading in Russian, which uses the Cyrillic script, is affected by phonological skills in beginner readers.
- Accuracy in phonological tests depends on the linguistic complexity of the tests, measured as the number of linguistic processes involved for successful performance.
- Complex phonological tests predict reading fluency better.

Implications for theory, policy or practice

- Advanced phonological skills need to be developed for successful reading acquisition.
- Linguistic complexity of the tests should be taken into account in the studies assessing the effect of phonological processing on reading skills.

The importance of phonological processing, that is, the mental operations involving phonemes (minimal distinctive linguistic sounds), for reading acquisition has been demonstrated by many studies (Berninger et al. 1987; Wagner & Torgesen 1987; Hogan et al. 2005; Del Campo et al. 2015). The theoretical model of phonological processing developed by Torgesen and Rashotte (1994) distinguishes three main components: phonological awareness, phonological working memory and rapid automatised naming. Many studies of reading rely on that model (Ramus et al. 2003; Knoop-van Campen et al. 2018, among others). There is a growing consensus among researchers that each of these components contributes to reading (Torgesen et al. 1994; Sunseth & Bowers 2002) and that the results in phonological tests addressing different phonological processing components are frequently highly intercorrelated (Wagner & Torgesen 1987; Parrila et al. 2004).

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Despite extensive research, it remains elusive which phonological tests are the most predictive for reading skills (Parrila et al. 2004; Georgiou et al. 2008). Even when they address the same component of phonological processing, some tests predict reading skills better than others. For example, Kilpatrick (2012) compared the impact of different phonological awareness tests on reading and reported a better association of the phonological manipulation evaluated by the elision test (deleting a sound from a word, e.g., saying 'drive' without /r/ – 'dive') than of the phonological segmentation test (separating words into their individual sounds, e.g., saying the word 'sat' one part at a time – /s/ /æ/ /t/) with reading. One of the most plausible explanations is that phonological tests may differ in their cognitive requirements (Backman 1983; Yopp 1988; Vandervelden & Siegel 1995). For instance, the spoonerisms test (switching the first sounds or syllables of the words, e.g., 'Santa Claus – Clanta Saus') may involve or not involve lexical access depending on whether multisyllabic words or pseudowords are used. At the same time, tests assessing different components of phonological processing may require an overlapping set of cognitive processes; for example, the spoonerism test used for testing phonological awareness and the nonwords repetition test used for testing phonological working memory both require speech perception, phonological decoding and working memory (Dandache et al. 2014).

In turn, reading and reading comprehension are complex multifaceted skills involving the orchestration of a number of cognitive processes (Luria 1966; Rayner & Reichle 2010; Tunmer & Hoover 2019). Multiple attempts to reflect the complex structure of involved cognitive processes were conducted in existing models of reading (Adams 1982; Rayner & Reichle 2010). Some cognitive processes involved in reading and reading comprehension, such as lexical access or working memory (Seidenberg & McClelland 1989; Vellutino et al. 2007), may also be involved in phonological processing tests for successful performance. Thus, phonological tests may involve a set of cognitive processes, partially overlapped with a set of processes required for successful reading. However, the idea that the overall complexity of a phonological test, regarded as a number of involved processes, affects its potential to predict reading skills has never been strictly tested.

To contribute to this field, we tested the relationship between the level of linguistic complexity of phonological tests and reading skills in Russian. For that, we developed seven phonological tests for Russian language varying in linguistic complexity (Table 1), for example, the number and type of involved linguistic processes. For each phonological test, we evaluated whether it recruits the following six linguistic processes: (1) input processing (speech perception and phonological decoding), (2) lexical access (only involved in processing of real words), (3) phonological working memory (notably engaged when there is a need to maintain phonological materials in memory to perform a task), (4) phonological analysis (the process of consciously dividing the speech stream into individual phonemes), (5) operations with phoneme sequences (phonological manipulations, such as deletion, substitution, or sound reversal, in terms of Kilpatrick 2012) and (6) output processing (phonological retrieval and articulation). The set of involved processes depends not only on the task but also on the test parameters, such as unit of word structure analysed (syllables, onsets, rimes or phonemes), stimulus modality (visual or auditory) or the makeup of the specific phonological task (Oron et al. 2016). As a result, our seven tests were classified as belonging to four levels of increasing complexity.

The simplest tests relied on two processes. The Phoneme Discrimination test (e.g., 'Are /fom/ and /pom/ the same?') only required input processing and phonological working memory (maintaining two pseudowords while making a judgement) and did not engage the other four processes, including lexical access (because we used only short nonwords).

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TABLE 1. Linguistic processes involved in seven phonological tests.

	Linguistic processes					
Tests	Input (speech perception, phonological decoding)	Lexical access	Phonological working memory	Phonological analysis	Operations with phoneme sequences	Output(phonological retrieval and articulation)
Phoneme discrimination (2)	+	–	+	–	–	–
Lexical decision (2)	+	+	–	–	–	–
Pseudoword repetition (3)	+	–	+	–	–	+
Phoneme detection (4)	+	+	+	+	–	–
Phoneme isolation (4)	+	+	–	+	–	+
Number of sounds (5)	+	+	+	+	–	+
Changing sound in a pseudoword (5)	+	–	+	+	+	+

The number in parenthesis on the left represents the postulated number of linguistic processes required to successfully pass the test. '+' reflects that the linguistic process is involved in the task.

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Similarly, the Lexical Decision test (e.g., 'Is/pulitsa/a real word?') – depended on input processing and lexical access. The more difficult Pseudoword Repetition test (e.g., "dzhuk" derived from "zhuk" [a beetle]) required three processes: output processing (phonological retrieval and articulation) in addition to the input processing and phonological working memory involved in the Phoneme Discrimination test. At the next level of complexity, four processes were required: The Phoneme Detection test (e.g., 'Is the sound/t/present in/table/?') engaged the input processing, lexical access, conscious phonological analysis and working memory (the participant had to hold the target sound in memory while listening to the entire word). The Phoneme Isolation test (where participants listened to a word and had to say out loud its first sound, e.g., 'gitara – /g'/') did not significantly charge phonological working memory but required input processing, lexical access, phonological analysis and output processing. The two most complex tests – Number of Sounds and Changing the Sound in a Pseudoword – involved five linguistic processes for successful performance. In the Number of Sounds test, the participant had to count the number of sounds in a word, using all the processes considered in Table 1, except for operations with phoneme sequences. The Changing Sound in Pseudoword test (where participants had to replace a specific phoneme in an auditorily presented pseudoword with another given phoneme, e.g., 'Replace the sound/b/with/p/' was followed by the pseudoword 'nuba', and the participant had to respond 'nupa') required all the processes except lexical access. We did not include the Rapid Automatised Naming test, which is often used for screening reading skills, because it is not purely phonological and involves visual processing. In our study, all tests were presented in the auditory format.

We expected the participant children to be less accurate in the more complex phonological tests. Critically, based on Kilpatrick's (2015) statement that instruction of *advanced* phonological skills is a key factor of a successful reading intervention, we also expected that the greater individual cost of adding one more linguistic process to the phonological task would be associated with lower reading fluency and reading comprehension. Conceptually, that would fit the hypothesis that the performance on complex phonological tests and reading (seen as a complex multifaceted process) involves an overlapping complex set of linguistic processes. However, the level of complexity required to trigger an association between test performance and reading skills was an empirical question to investigate.

It is also worth noticing that most of the reading research has been done on languages using the Latin script, and little is known about the role of phonological processing in reading based on Cyrillic orthography. Cross-linguistic studies showed that orthographic consistency modulates the rate of development and prevalent patterns of relative reading performance and impairment (Furnes & Samuelsson 2010; Ziegler et al. 2010; Marinelli et al. 2016; Diamanti et al. 2018; Ijuin & Wydell 2018). In terms of its grapheme-to-phoneme mappings, Russian has high orthographic transparency with certain exceptions and context-dependent rules (Kornev et al. 2010). Phoneme-to-grapheme conversion is opaque and involves a larger number of phonological principles that change the spelling (Boulware-Gooden et al. 2015). For example, the rules for reduction of unstressed vowels depend on the position of the stress but are more transparent than the rules for identifying the graphemes corresponding to reduced vowels ('воробей' /v.atrn;rɐ'bʲej/ [a sparrow], 'карандаш' /k.atrn;rɐn'daʂ/ [a pencil]); the same way voiced consonants at the end of the word are pronounced as voiceless ('код' /kot/ [a code], 'кот' /kot/ [a male cat]), and it is not transparent which grapheme should be written corresponding to voiceless consonant at the end of the words. One complication for beginner readers is that palatalised and nonpalatalised consonants are typically grouped with vowels of respective series,

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but there are multiple exceptions (Zhukova & Grigorenko 2019). Another complication is that a position of stress is arbitrary, and children learn it with increasing reading experience. Importantly, unstressed vowels undergo reduction, which can appear in the prefix, root or suffix of a word. Beginner readers are more likely to know the correct place of stress in high frequency words but may find it difficult for low frequency words. Instability of syllabic boundaries (Kerek & Niemi 2012), especially in multisyllabic words with consonant clusters (Starzhinskaya 1988), additionally slows down the acquisition of reading in Russian (for more details about Russian orthography and reading, see Zhukova & Grigorenko 2019).

The earliest descriptions of impaired phonological processing associated with impaired reading, in Russian, date back to the 1930s (Mnukhin 1934). In contemporary Russian speech therapy literature, a phonological processing deficit is acknowledged as one of the potential causes of reading impairment (Volkova 2007). Interestingly, the Russian speech therapy tradition particularly stresses that impaired phonological processing not only leads to reading dysfluency but also affects reading comprehension (Lalayeva & Venediktova 2001). One of the few available experimental studies in Russian showed that, in middle school students, phonological awareness has a higher predictive value for orthographic processing than rapid serial naming (Rakhlin et al. 2014). However, the relationship between phonological processing and reading skills in Russian beginner readers has never been experimentally investigated. Our study further contributes to the understanding of universal and language/script-specific aspects of phonological processing and its effect on reading.

Method

Participants

Study participants (Table 2) were recruited at three Russian public schools, two in Moscow ($N = 58$) and one in Volgograd ($N = 47$). All children (total $N = 105$) were native Russian speakers, 7 to 11 years-of-age, and were primary school students in the first through fourth grades. The participants had no history of diagnosed neurological and/or psychiatric disorders and no diagnosed problems with reading acquisition. All had normal or corrected-to-normal vision. Screening for primary auditory impairment (using Audiogramm version 4.6.1.3, Professional Audiometric System; Sennheiser HDA 280 audiometry headphones) resulted in exclusion of three participants. Screening for nonverbal intelligence with the Raven's (2004) Coloured Progressive Matrices resulted in the exclusion of 12 participants who scored below norms. Ninety children (48 girls; 7 left-handers; $M_{age} = 8.7$, $SD = 1.13$)

TABLE 2. Overview of participants.

Process	First graders		Second graders		Third graders		Fourth graders	
	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys
Tested	13	6	15	12	15	18	10	16
Excluded	1	0	0	0	2	5	2	5
Analysed	12	6	15	12	13	13	8	11

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remained in the analysis. The data from 20 of them, randomly selected, were used to assess the inter-rater (SD and VR) reliability of the phonological tests.

We have recruited additional 17 children to assess test–retest reliability of phonological tests at one Russian public school in Moscow. All were native Russian speakers, 10 to 11 years-of-age, and were primary school students in the fourth grade. The participants had no history of diagnosed neurological and/or psychiatric disorders; all had normal or corrected-to-normal vision. Screening for primary auditory impairment showed that all children had normal hearing. Screening for nonverbal intelligence with the Raven's (2004) resulted in the exclusion of one participant who scored below norms. Sixteen children (eight girls; $M_{age} = 10.1$; $SD = 0.13$) remained in the analysis. We administered the same tests to the same group of participants twice with an average interval of 24.6 days ($SD = 2.86$; range 22–30).

Written informed consent forms were signed by parents or legal representatives of the children, and children gave their assent prior to their inclusion in the study. The study was approved by the Committee on Interuniversity Surveys and Ethical Assessment of Empirical Research, National Research University Higher School of Economics (Russia).

Materials

Children's reading fluency and reading comprehension were assessed with a standardised test for reading in Russian (Kornev & Ishimova 2010). Children had to read aloud two texts (Text 1, 'Kak ja lovil rakov' [*How I caught crayfish*] and Text 2, 'Neblagodarnaja Yel' [*Ungrateful spruce*]) as quickly and accurately as possible, and to answer 10 content questions about factual information, explicitly mentioned in the texts. The first text (98 words) was simpler, with short, mostly high-frequency words; the second text (127 words) was more complicated, with a greater number of polysyllabic and low-frequency words (for more details on the reading test, see Dorofeeva et al. 2019). According to the guidelines of the test, reading fluency was measured as the number of words read accurately in the first minute, reading comprehension was measured as the number of correct question responses.

Phonological processing was assessed using the Russian Test of Phonological Processing (RuToPP), which includes the seven tests described below. All tests were programmed in Java SE 8 and administered using a Samsung Galaxy Tab A SM-T585 (2016) on Android 7.0 platform, screen size 10.1″, 1,920 × 1,200 px. Audio stimuli were pre□recorded by a professional speaker in a recording studio. In the comprehension tests (1–3), the accuracy of participants' responses was registered automatically. In the production tests (4–7), participants' vocal responses were automatically recorded by the same programme and analysed offline later by the examiner. Before each test, participants were instructed and completed three training trials that were not included in the analysis. Participants could ask questions and get clarification during training, but they received no feedback afterwards.

For all items that included existing Russian words, the words were selected from a database of psycholinguistic stimuli (Akinina et al. 2015), with age of acquisition below 6 years. In Tests 2–7, items were balanced on the number of syllables. For Test 1, we selected nine types of items according to the type of the first sound – the only one which differed in each pair of pseudowords (e.g., vowel/consonant palatalised/consonant sonor/consonant sibilant/etc.). The items of Test 2 were both words and pseudowords.

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For Tests 3–7, we selected three types of items: one-syllable, two-syllable and three-syllable items. In Tests 1, 2, and 6, items were presented in a pseudorandomised order; in Tests 3–5 and 7, one-syllable items were presented at the beginning of the test, with three-syllable items presented at the end. The order of items and test presentation was the same for all participants.

1 In the *Phoneme Discrimination* test, participants listened to pairs of three-phoneme pseudowords and had to judge whether they were the same or different by pressing the 'Yes' or 'No' button on the tablet screen. The pseudowords in each pair could differ only by the first sound. The test contained 42 pairs of pseudowords, 36 pairs with a CVC structure (e.g., 'vom-fom, vom-vom'; half of the pairs differed) and 6 pairs with a VCV structure (e.g., "uma-oma, aza-aza", half of the pairs were different, and the first syllable was always stressed).
2 In the *Lexical Decision* test, participants had to judge whether an item presented in audio form (three to eight phonemes, one to three syllables) was a word or a pseudoword. The test contained 24 items, half of them being pseudowords. The real words were of high frequency (Mean = 151.3; Range [80.1:304.3]). To emphasise the phonological component of this otherwise nonphonological test, the pseudowords were derived from real Russian words (also of high frequency) by changing, adding or deleting one phoneme (these are mistakes that are characteristic for children with reading disorders, according to the observations of Russian speech therapists; Lalayeva & Venediktova 2001 ; Volkova 2007); they followed the phonotactic patterns of Russian (e.g., 'ferjovka' derived from 'verjovka' [a rope], 'pulitsa' – from 'ulitsa' [a street], 'kadrat' – from 'kvadrat' [a square]). These resulted in minimal acoustic distinctions between pseudowords and their real word counterparts.
3 In the *Phoneme Detection* test, participants heard a phoneme followed by a word and had to press the 'Yes' button if the phoneme was present in the word, and 'No' otherwise. The test contained 24 one-to-three-syllable items, with the position of the target phoneme balanced between the beginning, the middle, or the end of the word (e.g., 'm' … m'ach' [a ball], 'sh … loshad'' [a horse], 'k … podarok' [a present]).
4 In the *Pseudoword Repetition* test, participants repeated pseudowords that were presented auditorily. The test contained 24 one-to-three-syllable items derived from real Russian words by changing, adding or deleting one phoneme or by swapping two adjoining phonemes. Such changes correspond to the errors reported by Russian speech therapists for Russian children with impaired reading skills (Lalayeva & Venediktova 2001; Volkova 2007). All items followed the phonotactic patterns of Russian (e.g., 'nopata' derived from 'lopata' [shovel], 'dzhuk' – from 'zhuk' [beetle], 'tarik' – from 'starik' [old person], 'konmata' – from 'komnata' [room]). Only responses with all phonemes produced properly were classified as correct.
5 In the *Phoneme Isolation* test, participants listened to a word and had to say out loud its first sound ('gitara – /g'/, nos – /n/, ozero – /o/'). The test contained 24 one-to-three-syllable items. In four items, the first sounds were vowels; 20 items had initial consonants, and among these 10 consonants were palatalised, with half of those 10 being voiceless. Only responses with the specified phonemes produced properly were classified as correct (e.g., if a palatalised sound was produced as unpalatalised or vice versa, the response was considered incorrect).
6 In the *Number of Sounds* test, participants listened to a word and had to say out loud the number of sounds in it. The test contained 24 words (three to eight phonemes, one to

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three syllables) with the number of sounds corresponding to the number of letters (e.g., 'kit' [whale] – three, 'slon' [elephant] – four, 'kletka' [cell] – six and 'pistolet' [gun] – eight).

7 In the *Changing Sound* test, participants had to replace a specific phoneme in an auditorily presented pseudoword with another given phoneme. For example, the instruction saying 'Replace sound/v'/with/v/' was followed by the pseudoword 'mimiv'a', and the participant had to respond 'mimiva'. The test contained 24 one-to-three-syllable items. The target phoneme was at the beginning in one-syllable items, in the middle in two-syllable items, and at the beginning of the last syllable in three-syllable items. In an equal number of items (three each), voiceless consonants had to be replaced by their voiced counterparts, and the other way around; palatalised – with unpalatalised, and the other way around; sonorous – with fricative, and the other way around; in six items, a vowel had to be replaced with another vowel. Only responses with all phonemes produced properly were classified as correct.

Reliability of phonological tests

We assessed the test–retest reliability of all seven phonological tests and the inter-rater reliability of four production phonological tests (4–7), because, in the comprehension tests (1–3), the accuracy of participants' responses was registered automatically. Statistical analysis of test–retest reliability and inter-rater reliability was carried out using the 'psych' package for R (Revelle 2020). The data and the analysis code can be downloaded from the Open Science Framework (https://doi.org/10.17605/OSF.IO/S8X3M). Because the data were not normally distributed, statistical testing was performed nonparametrically. The results of the Wilcoxon signed-rank test with continuity correction showed no significant difference between the performance of participants at the first and second testing time points (Table 3). The results indicated a high test–retest reliability of each of the seven phonological tests. To measure the inter-rater reliability, the Spearman's correlation coefficients were calculated. The inter-rater reliability measures (Table 4) demonstrated that the two raters highly agreed in their scoring, showing that the scoring system is reliable.

TABLE 3. Analysis of test–retest reliability of phonological tests.

Phonological tests	Test 1 mean accuracy	Test 2 mean accuracy	Wilcoxon signed-rank test	
			V value	*p* value
Phoneme discrimination	0.97	0.97	15	0.72
Lexical decision	0.93	0.96	3	0.07
Phoneme detection	0.94	0.94	28.5	0.51
Pseudoword repetition	0.91	0.90	39	0.26
Phoneme isolation	0.87	0.89	8	0.10
Number of sounds	0.84	0.83	56.5	0.46
Changing sound	0.86	0.89	11	0.10

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TABLE 4. Analysis of inter-rater reliability of phonological tests (means and Spearman correlations with confidence intervals).

Phonological test	Rater 1 (Mean)	Rater 2 (Mean)	r_s	95% CI
Pseudoword repetition	0.87	0.86	0.96**	[0.89, 0.98]
Phoneme isolation	0.88	0.87	0.98**	[0.95, 0.99]
Number of sounds	0.92	0.92	0.99**	[0.98, 1.00]
Changing sound	0.91	0.90	0.98**	[0.94, 0.99]

95% CI indicates 95% confidence interval for each correlation.
*$p < .05$.
**$p < .01$.

Procedure

The data were collected over one-on-one sessions between the participant and the researcher. Three researchers, all professional linguists, trained to work with young children, were involved in the data collection. The total duration of each session varied between 40 and 60 minutes, including breaks when needed. The testing took place in a quiet classroom.

Screening for primary auditory impairment (using the program Audiogramm version 4.6.1.3, Professional Audiometric System; Sennheiser HDA 280 audiometry headphones) was administered first. Afterwards, participants read two texts from a standardised test for reading in Russian (Kornev & Ishimova 2010) and answered 10 content-related questions after reading each text. We audio-recorded children while they were reading; these records were further analysed offline. Seven phonological tests were administered afterwards, from the easiest Phoneme Discrimination test to the most complex Changing Sound in Pseudoword test. Screening for nonverbal intelligence with the Raven's (2004) Coloured Progressive Matrices was administered at the final stage. The order of test presentation was the same for all participants. After all the tests, a participating child received a small present.

Results

The data were analysed using (generalised) linear mixed models estimated in a Bayesian framework using the 'brms' package for R (Bürkner 2017). We report effects whose 95% credible intervals do not include 0. The data and the analysis code can be downloaded from the Open Science Framework (https://doi.org/10.17605/OSF.IO/S8X3M).

To assess whether phonological tests which require more linguistic processes are harder, we built a model with a binomial link function, using the accuracy in each probe as a dependent variable, and the following predictors: the number of processes in the test the probe belonged to (centred at 3, hence the intercept estimated performance in the Pseudoword Repetition test), the child's grade (the intercept estimated performance of the first-graders), gender (intercept corresponding to girls) and Raven score (centred and scaled). We also included a three-way interaction between the number of processes, grade and gender, as well as all two-way interactions included in it, to test whether the effect of the number of processes changed across grades or depended on gender. We used weakly

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informative priors for all predictors (Normal(0, 0.3)). The model included random intercepts for tests (thus capturing the variance associated with all aspects of individual tests other than the number of linguistic processes involved), individual probes, item types and participants, as well as by-participant random slopes for the number of processes. From this model, for each child, we extracted the individual estimate of decrease in accuracy (in logits) associated with introducing one more linguistic process to a phonological test.

The second stage of the analysis assessed whether the cost of a linguistic process, estimated for each child at the previous stage, is associated with this child's reading fluency and comprehension. The dependent variables in these analyses were the number of words read (we assumed underlying negative binomial distribution) and the accuracy of question responses (using binomial link function) for each of the two texts. The predictors were the estimated cost of a linguistic process, grade (intercept corresponding to the first grade), gender (intercept corresponding to girls) and Raven score (centred and scaled). For the models estimating the accuracy of question responses, the (centred and scaled) number of words from the corresponding text read in the first minute was additionally included as a predictor. Weakly informative priors for the predictors were used in all models (Normal(0, 0.6)). The models estimating the accuracy of question responses also included random intercepts for individual questions as well as by-question random slopes for all the main effects present in the model.

Relative difficulty of phonological tests

The mean proportion of incorrect answers in each test is presented on Figure 1. Analysis of the relative difficulty of the tests revealed a negative main effect of adding one more linguistic process to a phonological test (Table 5): accuracy decreased with increasing number of linguistic processes. The estimated accuracies, depending on the number of processes in tests, are presented on Figure 2. Surprisingly, there was no effect of grade,

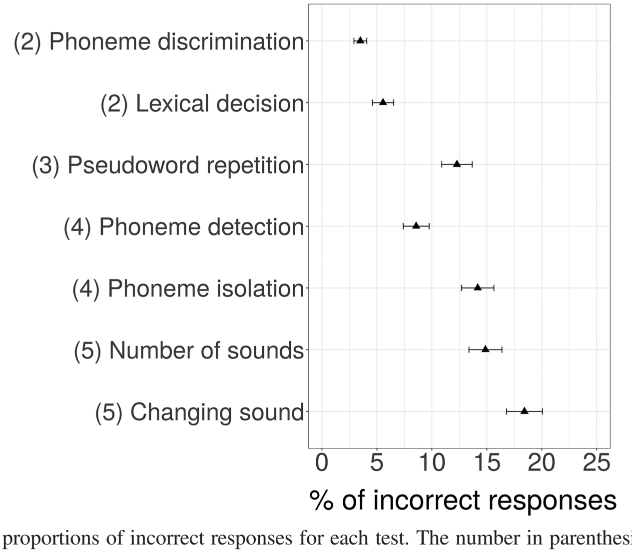

FIGURE 1. Mean proportions of incorrect responses for each test. The number in parenthesis on the left represents the postulated number of linguistic processes required to successfully pass the test.

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TABLE 5. Analysis of probe response accuracy.

Predictor	Estimate (on log-odds scale)	95% credible interval
Intercept (three linguistic processes, girls, first school year)	3.27	2.67 to 3.75
Additional process	**−0.60**	**−0.93 to −0.15**
Grade	0.04	−0.11 to 0.21
Boys	−0.29	−0.62 to 0.05
Raven	**0.15**	**0.02 to 0.28**
Additional process × grade	0.09	−0.04 to 0.22
Additional process × boys	−0.15	−0.45 to 0.14
Boys × grade	0.10	−0.10 to 0.29
Additional process × grade × boys	0.12	−0.05 to 0.29

Values in the rows below Intercept show how the estimate for correct responses (Intercept) changes depending on a particular value of the predictor. Ninety-five credible intervals (CrIs) quantify our uncertainty about the estimated parameter: we are 95% certain that the true value of the parameter lies within this interval. Effects whose 95% CrI exclude 0 are in bold.

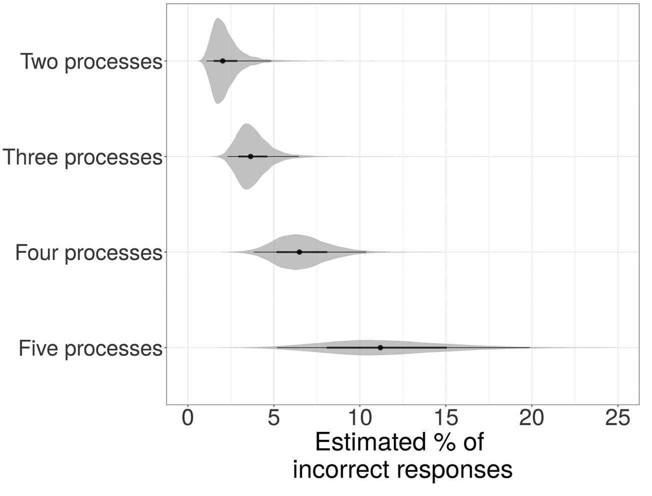

FIGURE 2. Estimated accuracy and 95% credible interval (CrI) (black lines) on a test as a function of the number of linguistic processes involved in the test.

but higher Raven scores were associated with higher accuracy. We also found some indication of gender differences: during the first year of school, boys tended to perform worse than girls (Prob($\beta < 0$) = 0.95). No interactions were reliable. The individual costs of adding one more linguistic process to the test, estimated by the model, for each participant are presented on Figure 3.

Reading assessment

For the simpler text (Table 6), greater individual cost of an added linguistic process was associated with lower reading fluency, while higher grade and Raven scores were

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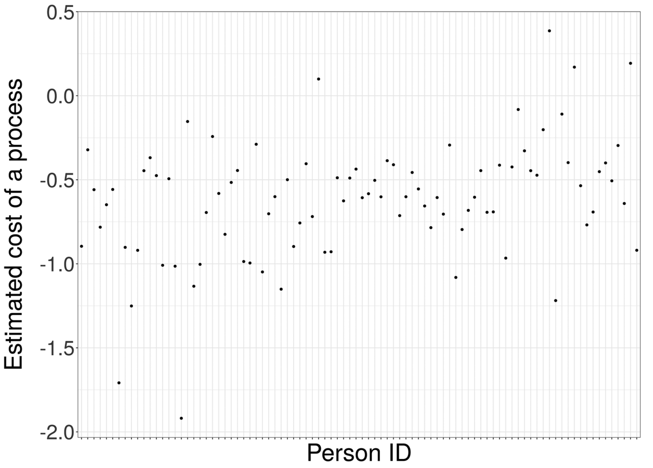

FIGURE 3. Estimated individual costs (on the log-odds scale) of adding one more linguistic process to a phonological test. For the majority of the participants, an additional linguistic process, added to a phonological test, decreases accuracy on that test.

associated with higher fluency. Question response accuracy tended to increase with greater reading fluency (Prob($\beta > 0$) = 0.96), but other predictors did not affect it.

For the more complex text (Table 6), again, the greater individual cost of an added linguistic process was associated with lower reading fluency. Fluency increased with grade and tended to increase with higher Raven scores (Prob($\beta > 0$) = 0.96). Question response accuracy was lower in boys and higher in children with higher Raven score. There was some indication that accuracy increased with grade (Prob($\beta > 0$) = 0.96).

To summarise, for both texts, a greater individual cost of a linguistic process, required for a phonological test, was associated with a reliable decrease in reading fluency, while higher grade and higher Raven scores were associated with greater fluency. The picture for reading comprehension, measured as question response accuracies, was not so clear-cut: most importantly, there was no indication that accuracy depended on the individual cost of a linguistic process in the phonological tests.

Discussion

This study examined whether the level of complexity of phonological tests influenced the ability of these tests to predict reading skills (fluency and comprehension) in 7-to-11-year-old typically developing Russian children. The tests assessing phonological processing were designed and ranked according to the number of involved linguistic processes. The present study contributes to the current body of literature on the relationship between phonological processing and reading by systematically investigating the impact of phonological processing complexity on reading proficiency in Russian.

We expected the participants to be less accurate in the more complex phonological tests, and we found that this is indeed the case. Additionally, for each child, we extracted the individual estimate of decrease in accuracy, associated with introducing one more linguistic process to a phonological test, and assessed whether this individual cost was associated with the child's reading fluency and comprehension. Greater costs were reliably associated

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TABLE 6. Statistical modelling results for Texts 1 and 2.

Predictor	Text 1 (simpler)				Text 2 (more difficult)			
	Number of words read correctly		Question response accuracy		Number of words read correctly		Question response accuracy	
	Estimate (log-mean)	95% CrI	Estimate (log-odds)	95% CrI	Estimate (log-mean)	95% CrI	Estimate (log-odds)	95% CrI
Intercept	4.12	3.96 to 4.29	1.38	0.33–2.50	3.78	3.59 to 3.98	−0.08	−0.98 to 0.85
Cost of a linguistic process	**−0.15**	**−0.29 to −0.01**	−0.05	−0.58 to 0.52	**−0.16**	**−0.33 to −0.00**	−0.23	−0.73 to 0.26
Gender: boys	−0.01	−0.11 to 0.08	−0.36	−0.76 to 0.10	0.00	−0.10 to 0.11	**−0.53**	**−0.95 to −0.12**
Grade	**0.23**	**0.22 to 0.23**	0.12	−0.22 to 0.58	**0.32**	**0.27 to 0.38**	0.26	−0.04 to 0.56
Raven score	**0.06**	**0.01 to 0.11**	−0.02	−0.25 to 0.20	0.05	−0.01 to 0.11	**0.21**	**0.00 to 0.41**
Reading fluency			0.34	−0.05 to 0.82			−0.08	−0.35 to 0.21

Ninety-five credible intervals (CrIs) quantify our uncertainty about the estimated parameter: we are 95% certain that the true value of the parameter lies within this interval. Effects whose 95% CrI exclude 0 are in bold.

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with a decrease in reading fluency, both in simpler and more difficult texts. These findings suggest that the linguistic processes involved in complex phonological operations and reading overlap in beginner readers. Our result is in line with the findings of Kilpatrick (2015), who showed that reading intervention success depends on the explicit instruction of *advanced* phonological skills. It also explains the significant correlation between the spoonerisms task (featuring a high level of complexity) and reading (Ramus et al. 2003; Law et al. 2014), as well as varying degrees of correlation between reading proficiency and tasks targeting the same traditionally distinguished component (Del Campo et al. 2015). Indeed, the more complex phonological manipulation task predicts reading proficiency better than the less complex phonological segmentation task (Kilpatrick 2012).

We also showed that higher grade and higher Raven scores were associated with greater reading fluency in Russian primary school children. Higher Raven scores were also associated with higher accuracy in phonological tests and better reading comprehension of more difficult text. Surprisingly, there was no effect of grade on the accuracy in phonological tests. The reason might be that the accuracy was close to the ceiling even in the first graders, especially in the tests with a smaller number of linguistic processes involved. These findings show that typically developing primary school children are overall highly proficient in phonological processing, with only advanced phonological skills being vulnerable at this age. Future studies are needed to investigate phonological skills in preschool children and to analyse to what extent early development of phonological skills can predict reading acquisition in Russian.

We did not find evidence that successful phonological processing is associated with higher reading comprehension, measured as question response accuracy. This does not mean that there is no relationship between phonological processing and reading comprehension, but the nature of this relationship, in Russian, remains an open question. Russian speech therapists particularly stress the important role of phonological processing, both for reading fluency and reading comprehension (Lalayeva & Venediktova 2001; Volkova 2007). Reading fluency is a vehicle for text comprehension, but the latter requires more linguistic and general cognitive skills (Cain & Oakhill 2006). Taking into account the significance of the ability to comprehend what is read for further educational progress in primary school students, the exact contribution of phonological processing to ultimate reading comprehension deserves more investigation. One of the possible ways to do it is to conduct a similar study with a more detailed reading comprehension test (e.g., with questions asked after each sentence read, not after the text, or with linguistically balanced questions targeting different syntactic constructions). In addition, there is a growing evidence of the important role of morphological awareness for reading comprehension (Deacon et al. 2018; To et al., 2014), so the combined impact of phonological and morphological processing on reading comprehension in languages with reach morphology such as Russian needs to be tested in the future.

To acknowledge the limitations of the study, we admit that the designed phonological tests only reflect four levels of complexity, because we aimed to consider different types of linguistic processes while still making the test battery feasible. Additionally, the classification of the processes involved in the used tasks could be more detailed and include non-linguistic cognitive processes. Furthermore, because of a lack of a standardised word reading test in Russian, we could not assess word-level reading skills in the tested children. Therefore, only text-level reading skills were addressed. The absence of a standardised reading comprehension test in Russian, with linguistically balanced questions, is an additional limitation.

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Despite its limitations, the present study not only confirms the important role of phonological processing for reading, in Russian, but also provides experimental evidence to the debate on the most appropriate phonological tests for studies of reading, stressing a higher predictive value of more complex phonological tests for reading fluency (Parrila et al. 2004; Georgiou et al. 2008). It is of theoretical interest to examine, more deeply, the component functions in phonological tasks, in order to more fully understand which elements of phonological processing relate specifically to reading fluency and reading comprehension. The cognitive requirements of the behavioural tests (phonological tests, comprehension tests etc.) should be considered more carefully while choosing tests for future studies. For example, for studies assessing the role of morphological processing in reading fluency, in contrast to phonological processing, it would be important to take into account the linguistic processes involved in chosen phonological and morphological tests, because the overlap of linguistic processes involved in the tests used, may impact the amount of variance in the reading fluency explained by these tests.

Our study may have important implications for practitioners, both for diagnosing underlying mechanisms of reading impairment and for reading intervention programmes. For diagnostic purposes, it is important because phonological processing tests that target the underlying processes could help to identify the locus of a deficit in reading disorders associated with phonological impairment. Therefore, similar studies involving children with dyslexia would be encouraged. For reading intervention programmes, it is relevant because the confirmed association between complex phonological tests and reading, in Russian, underlies the important role of training *advanced* phonological skills for reading intervention (in line with Kilpatrick 2015).

We admit that our results cannot automatically be generalised to other languages. According to the grain-gaze theory (Ziegler & Goswami 2005), phonological processing strategies in reading can differ across orthographies (shallow vs. deep). However, we believe that our approach can be extended easily to other alphabetic languages. Future studies are needed to determine how well our results generalise to other languages and how the association between individual cost of a linguistic process required for a phonological test and reading skills depends on orthographic transparency.

Acknowledgements

We gratefully acknowledge the help of L. A. Pushkareva and E. I. Larionova (a psychologist and the Director of School 556 of the Southern District of Moscow, Russia), A.V. Kornilov (the Department Head of School 1236 named after S. V. Milashenkov, Moscow, Russia), N. Volovik and M. Sukiasyan (the Assistant Director and the Director of General School ‘Pokolenie’, Volgograd, Russia). We are thankful to all the children who took part in this research and to their parents. We also thank the anonymous reviewers for their constructive feedback that helped to improve this work.

Funding

This study was performed with financial support from the Russian Foundation for Basic Research, Project No. 17-29-09122. The contribution of Victoria Reshetnikova and Wim

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Tops was funded by the Center for Language and Brain NRU Higher School of Economics, RF Government Grant, ag. No. 14.641.31.0004.

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Received 27 August 2019; revised version received 14 July 2020.

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