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Individual differences in L2 acquisition of English phonology: The relation between cognitive abilities and phonological processing☆

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ABSTRACT

Research on individual differences has identified factors constraining second language (L2) acquisition in terms of a global performance; yet little progress has been made in identifying specific predictors of phonological acquisition. To explore potential predictors, we assessed cognitive abilities (working memory, attention control, processing speed) and lexical knowledge in L1 and/or L2. These measures were then correlated to overall individual L2-phonological acquisition scores, which were obtained by combining the scores from three phonological processing tasks, quantifying the acquisition of English phonological dimensions which are problematic for Korean L2 learners of English.

Thirty Korean learners of English and fifteen English native speakers participated in the study. Individual L2-phonological scores were most strongly correlated with measures of working memory in L2. The observed relationships indicate that individuals with a higher working memory capacity, and to some extent higher processing speed, had developed a more native-like phonological processing in L2. None of the demographic background measures was correlated with phonological processing.

1. Introduction

Every element of phonological knowledge in the native language (L1) automatically and unconsciously shapes speech perception and word recognition (for a review, see Sebastián-Gallés, 2005). The use of L1 phonological knowledge is pervasive and cannot easily be inhibited when processing input in a second language (L2). We call this phenomenon "L1-based processing", characterized by interference or transfer from L1 phonological knowledge during non-native or L2 processing (see Ellis, 2006). Optimal speech processing and efficient word recognition in the L2 is dependent on the development of a complete L2 phonological system that will effectively limit the influence of the L1 knowledge during processing. In the present study, we operationalize such reduction of L1-based processing as more native-like phonological processing in L2.

Even though the psycholinguistic literature does not usually emphasize any variability in individual performance, large differences in performance among L2 learners can be observed even in homogenous participant groups (Díaz, Mitterer, Broersma, & Sebastián-Gallés, 2012). Extensive research has been conducted about some of the factors underlying individual differences among L2 learners (Dörnyei, 2005). Among them, cognitive variables such as working memory (Miyake & Friedman, 1998), attention (Segalowitz & Frenkiel-Fishman, 2005), inhibitory control (Blumenfeld & Marian, 2013; Mercier, Pivneva, & Titone, 2013), vocabulary size (Majerus, Poncelet, Van der Linden, & Weekes, 2008), and processing speed (Golestani, Molko, Dehaene, LeBihan, & Pallier, 2007) have been associated with higher L2 proficiency and more efficient L2 processing (see also Costa & Santesteban, 2004; Festman, Rodriguez-Fornells, & Münte, 2010; Rodriguez-Fornells, Balaguer, & Münte, 2006).

Generally, higher cognitive performance is thought to enhance the quality of the input or facilitate specific learning mechanisms: for example, larger working memory capacity might allow learners more time to process and learn from the input by maintaining longer access to it, and better storage quality might promote more accurate

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perception (Goldstone, 1998) and learning. However, most studies have examined these factors as potential predictors of L2 acquisition in general rather than as predictors of L2 phonological processing. Regarding phonological processing specifically, recent research also indicates that some of these cognitive abilities might be related to more accurate pronunciation and phonological processing (Aliaga-Garcia, Mora, & Cerviño-Povedano, 2011; Darcy, Mora, & Daidone, 2014; Bundgaard-Nielsen, Best, & Tyler, 2011; Lev-Ari & Peperkamp, 2013; Safronova & Mora, 2012). These studies mostly target one cognitive variable or one or two isolated dimensions of phonological systems (e.g., vowel categorization).

The goal of the present study is to explore with a much broader scope the potential link between a number of factors mentioned above and individual differences in L2 phonological acquisition. We measured individual differences in phonological processing in three perception tasks targeting different areas of phonological representation in the L2 (phonetic categories, complex word onsets, and word stress). Participants took part in a battery of tests designed to measure cognitive abilities in three areas (working memory, attention control, processing speed), and lexical knowledge. We also recorded important demographic information and assessed executive functions using the Behavior Rating Inventory of Executive Function for adults (BRIEF-A; Roth, Isquith, & Gioia, 2005).

1.1. Working memory

Short-term and working memory (WM) vary among individuals (Baddeley, 2003; Cowan, 2010) and may underlie individual differences in language acquisition (Daneman & Carpenter, 1980; Miyake & Friedman, 1998). Previous studies found that a higher working memory is linked to larger vocabulary size in L2 (Papagno & Vallar, 1995), and correlates with more accurate perception of L2 vowels (Aliaga-Garcia et al., 2011). Establishing new and robust phonological representations requires learners to learn from the input. By allowing learners to maintain all the relevant pieces of information simultaneously active, higher functioning WM may facilitate the processing of rapid spoken input, allow for more precise traces of what was heard, and benefit phonological development.

1.2. Attention control

Learners need to allocate their attention to select relevant dimensions (*selective attention*) in the input for making certain linguistic (e.g., lexical, phonemic) distinctions and switch rapidly from one dimension to another (*attentional flexibility or control*). Attentional control is generally thought to play an important role in L2 learning, along with selective attention (Ellis, 2006; Francis, Baldwin, & Nusbaum, 2000; Goldstone, 1998). Segalowitz and Frenkiel-Fishman (2005) demonstrated a link between attentional control and L2 proficiency. This ability appears to be potentially very important for the success of L2 phonological learning, because individuals with more efficient attentional control will be able to bring relevant information to the foreground while bringing irrelevant information to the background, thereby allowing perceptual learning. Only very few studies focusing on L2 phonological development examine individual differences in attention control (Safronova & Mora, 2012).

1.3. Processing speed

Previous findings suggest that higher processing speed/efficiency is potentially involved in more efficient speech processing (Golestani et al., 2007). More efficient processing would leave more resources available for handling incoming subsequent input (Salthouse, 1996), thus generally preventing overload in phonological short-term memory, which is proposed as being critical to phonological learning (Miyake & Friedman, 1998).

Table 1
Summary of demographic characteristics of the participant groups.

Measure	Group	*M*	SD	Lowest	Highest
Age at testing (years)	Inexperienced	24.9	4.4	20	37
	Experienced	30.9	6.0	23	47
	NE	21.9	6.6	18	45
Age of arrival (years)	Inexperienced	24.3	4.4	20	36
	Experienced	26.1	5.9	17	41
Current L1 use (%)	Inexperienced	58.0	21.4	10	90
	Experienced	44.3	22.7	20	95
Current L2 use (%)	Inexperienced	38.7	20.7	10	90
	Experienced	55.7	22.7	5	80
Length of residence (months)	Inexperienced	6.1	5.0	2	16
	Experienced	46.6	23.2	21	100
Motivation (1–11)	Inexperienced	8.6	1.0	7.5	10.4
	Experienced	8.7	1.4	5.1	10.4

Note: Length of residence refers to the amount of time spent in the United States; Inexperienced = Inexperienced group; Experienced = Experienced group; NE = Native English speakers; motivation was about acquiring "good pronunciation in English" (see Supplement A).

1.4. Lexical knowledge

Phonological knowledge is closely connected to lexicon size and lexical connectivity. According to one view (Munson, Edwards, & Beckman, 2005a,b), phonological knowledge is an emergent property of lexical growth: phonological processing improves as the lexicon grows, leading to better abstraction of phonological regularities. Conversely, increasingly well-specified phonological representations are a reliable marker of better word learning. This relationship has only been investigated within the same language (e.g., L1 vocabulary size and L1 phonological knowledge or L2 vocabulary size and L2 phonological knowledge). Some studies (Bundgaard-Nielsen et al., 2011; Majerus et al., 2008; Tamati, 2014) suggest that a larger vocabulary in L2 allows for a more efficient abstraction of phonological regularities. However, one inherent confound of this approach is the inseparability between L2 vocabulary size and L2 proficiency. Therefore, we also investigate the potential relationship between L1 vocabulary size and L2 phonological knowledge.

Table 2
Overview of task order for each participant group.

Korean participants		English participants
Session 1	Session 2	Session 1
K Hearing screening	E Forward digit span	E Hearing screening
K Background questionnaire	E Backward digit span	E Background questionnaire
BRIEF-A	E Sentence repetition	*Break*
Break	E Forward non-word span	E Forward digit span
K Forward digit span	E Backward non-word span	E Backward digit span
K Backward digit span	*Break*	E Sentence repetition
K Sentence repetition	Phonological task 1	E Forward non-word span
K Paired associates	Phonological task 2	E Backward non-word span
K Forward non-word span	Phonological task 3	*Break*
K Backward non-word span	*Break*	E Naming
K Processing speed	E Production	E Attention
Break	K Production	*Break*
K Naming		Perception task 1
E Naming		Perception task 2
E Attention		Perception task 3
		NO production
Experimenter: native Korean speaker	Experimenter: native English speaker	Experimenter: native English speaker

Note: E = task conducted in English; K = task conducted in Korean; BRIEF-A = Behavior Rating Inventory of Executive Function, Adult Version (Roth et al., 2006). All participants followed this protocol with the exception of one Korean who performed K and E naming in session 2, and another Korean who performed E naming in session 2.

Table 3
Sample trial sequence for the attention control task with correct responses and trial type. Trial order is from left to right, then down.

nb.	Stimulus, *question*	Correct response	Trial type	nb.	Stimulus, *question*	Correct response	Trial type
1	Female voice, word *word?*	Yes	First	2	Male voice, word *word?*	Yes	No–shift
3	Male voice, word *male voice?*	Yes	Shift	4	Male voice, word *word?*	Yes	Shift
5	Female voice, nonword *word?*	No	No–shift	6	Female voice, word *word?*	Yes	No–shift
7	Female voice, word *male voice?*	No	Shift	8	Female voice, word *male voice?*	No	No–shift

Note: nb = trial sequential number.

2. The current study

Our phonological tasks were designed to measure how effectively a learner can reduce the influence of the L1 during L2 processing. If this influence is completely absent during L2 phonological processing, learners' performance on our tasks should be similar to that of English native speakers. From this performance, we computed a normalized composite measure, the *overall phonological score*, which we interpret as how efficiently a learner reduces the influence of the L1 while processing the L2. We then examine whether individual differences in cognitive abilities are related to differences in phonological score.

2.1. Participants

To determine a sufficient sample size, a power analysis was performed and revealed that 15 participants in each bilingual group would yield a power higher than .8 for correlations at $r = .500$. This is considered sufficient power for most analyses. Forty-five students at an American university participated in return for course credit or small payment. Fifteen participants spoke English as their L1 and were tested as controls (henceforth, NE group). Thirty participants spoke Korean as their L1 and were learners of English. All learners were living in the U.S. at the time of testing, either for less than eighteen months (Inexperienced group), or for more (Experienced group) (see Table 1).

A series of independent samples *t*-tests with the significance threshold set at $\alpha = 0.05$ examined whether both learner groups differed significantly on these variables. There was no difference between the groups with regard to the examined variables, except in current use of the L2, $t(28) = 2.14$, $p = 0.041$, and expectedly, in length of residence (LOR), $t(15.3) = 6.61$, $p < 0.001$. For all measures except LOR, groups displayed an overlapping range of inter-individual variation. Note that the Experienced group was older than the NE group ($p < 0.001$); the two learner groups did not differ in age. Twenty-seven participants knew one or more languages besides English, for which no-one reported high proficiency.

2.2. Experimental design

There were four categories of tasks, which will be explained below: 1) *General* (hearing screening; BRIEF-A; background questionnaire), 2) *Cognitive* tasks (simple and complex span tasks; processing speed; attention control), 3) *Lexical knowledge*, and 4) *Phonological processing.*

All participants were tested individually in a psycholinguistics laboratory: the English native speakers in a single session and the Korean native speakers in two sessions separated by a few days. The experimenter scored the participants' answers in a prepared scoring booklet. All testing sessions were audio-recorded to allow for later consistency checks in manual scoring.

General tasks were administered in the L1 of the participants. *Cognitive* and *lexical knowledge* tasks were administered in both Korean (L1) and English (L2) for Korean participants with the exception of processing speed (Korean/L1 only), and attention control (English/L2 only). *Phonological processing* tested perception of English phonological elements (Korean participants' speech samples were also recorded, in both Korean and English, but are not reported here). English participants were only tested in English for all tasks. In total, the Korean participants took part in 23 tasks, the English participants in 12. Table 2 summarizes the order of tasks. The order of task presentation was fixed and blocked by language as much as possible to avoid language interference induced by the testing situation (which might inflate the influence of L1 during processing). We were unable to perfectly balance the tasks because we wanted to keep all testing sessions to a similar duration. The Korean participants first took part in the general tasks, and then completed all cognitive tasks in L1, followed by the lexical knowledge and the attention control tasks. In the following session, they completed the cognitive tasks in L2, followed by phonological processing and the recordings. The order of tasks for English participants was very similar with minimal differences. All testing materials were recorded by native speakers of each language (i.e., Korean: Standard Seoul/Kyeonggi dialect; English: Midwestern dialect). The following section presents the details of the tasks.

2.2.1. General

2.2.1.1. BRIEF-A. The questionnaire (standardized rating scale of behaviors associated with specific domains of executive functions) was administered in English, with a Korean translation (only necessary in a few cases).

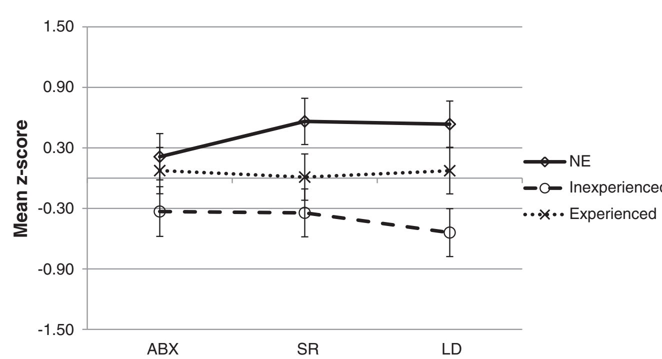

Fig. 1. Mean z-score per group on the control condition for each task (common contrasts for ABX, phonemic sequences for SR, and baseline items for LD). Error bars represent one standard error (SR = Sequence Repetition; LD = Lexical Decision).

Table 4
Summary of descriptive statistics for the test condition of each task.

		N	Mean z-score	SD	SE	95% CI (lower)	95% CI (upper)	Min.	Max.
Segmentals (ABX)	Inexp.	12	−0.70	.61	.18	−1.09	−.31	−1.57	0.41
	Experienced	14	−0.45	.64	.17	−.82	−.08	−1.93	0.48
	NE	15	1.11	.47	.12	.85	1.37	−0.10	1.73
Stress (SR)	Inexp.	14	−0.28	1.07	.29	−.90	.34	−2.53	1.15
	Experienced	15	0.08	.99	.26	−.46	.63	−1.92	1.35
	NE	15	0.25	.92	.24	−.26	.76	−1.51	1.35
Phonotactics (LD)	Inexp.	14	−0.53	.73	.20	−.95	−.11	−1.37	0.80
	Experienced	15	−0.36	1.04	.27	−.94	.21	−2.20	1.13
	NE	15	0.91	.48	.13	.64	1.17	−0.62	1.30
Phonological score (overall z-score)	Inexp.	15	−0.56	.54	.14	−.86	−.26	−1.85	.23
	Experienced	15	−0.27	.69	.18	−.65	.12	−1.68	.72
	NE	15	0.76	.45	.12	.51	1.00	−.21	1.46

Note: Inexp. = Inexperienced learners; Experienced = Experienced learners; NE = Native English speakers; SR = sequence repetition; LD = lexical decision; SD = standard deviation; SE = standard error; CI = confidence interval.

2.2.1.2. Background questionnaire. Participants filled out a questionnaire detailing their language learning and residential history, as well as motivation and patterns of current and recent language use. Details of central variables are presented in Table 1.

2.2.1.3. Hearing screening. All participants passed a pure-tone hearing screening (Reilly, Troiani, Grossman, & Wingfield, 2007) before taking part in the study.

2.2.2. Cognitive tasks

2.2.2.1. Working memory

2.2.2.1.1. Simple span tasks. We assessed the participants' phonological short-term memory storage capacity both in L1 (Korean) and L2 (English) using forward digit, backward digit, forward non-word, and backward non-word recall tasks. After listening to a series of digits or non-words played through a loudspeaker, participants verbally recalled the numbers or non-words in correct serial (forward or backward) order. Series length increased from three to ten items with two trials at each length. Overall scores were determined as the sum of scores for all correctly recalled trials across forward and backward tasks to allow for a more fine-grained differentiation between participants. A perfect recall of all trials on both forward and backward tasks would correspond to 208.

2.2.2.1.2. Complex span tasks. The first task was a sentence repetition test with last word recall (Alloway, 2007; Alloway, Gathercole, Kirkwood, & Elliott, 2009; Daneman & Carpenter, 1980), administered in L1 (to all participants) and L2. Scoring was based on the number of words recalled in the correct serial order (see examples in Supplement B). Trials for which sentences were not understood/could not be correctly repeated did not count towards the score.

The second task was a paired-associates learning task adapted from Majerus et al. (2008), administered in L1 to the Korean participants only. Participants were required to memorize the association between a cue word (Korean words) and a target item (a Korean word in Block 1, or an English non-word in Block 2). After presenting all pairs, the cue words were presented alone in a random order, and the participant verbally recalled the associated target item. Scoring was based on the number of phonemes correctly recalled in Block 2 only (maximum: 36). This task assesses the precision (quality) of storage for L2/novel items (see item list in Supplement C).

2.2.2.2. Attention control. To measure how easily a learner can shift her attention between various dimensions contained in spoken language, we used an attention control task targeting voice identity for indexical information (male or female voice), and a lexical dimension (word or non-word). One male and one female English native speakers' recorded stimuli consisting of frequent English words and phonotactically legal (in English) non-words. At each trial, participants answered "yes" or "no" to either of two questions (*Word*?; *Male voice*?) with respect to the item heard. A trial consisted of the following sequence: fixation (500 ms) → question (e.g., *Word*?) (500 ms) → auditory stimulus (e.g., "beach"). The answer to this example question would be "yes". Table 3 provides examples of trial sequences for this task.

The inter-trial interval was set to 1500 ms and response time-out was 3000 ms. Trials were pseudo-randomized and coded as "no-shift" (e.g., "word"-trial following a "word"-trial) or "shift" trials, depending on the nature of the question asked in the preceding trial, with the restriction that a maximum of 8 no-shift or shift trials could occur in a row. For the participants, the sequence of alternations between shift and no-shift trials appeared unpredictable (unlike Segalowitz & Frenkiel-Fishman, 2005). The no-shift trials formed the baseline condition. We measured accuracy and reaction time (RT) on shift vs. no-shift trials, and a measure of attention control efficiency was computed from the RT for correct answers only (shift cost).

On any shift trial, a participant may persevere on the same dimension regardless of the new question. This may yield an error and/or a slower RT depending on the nature of the stimulus presented ("type 1" trials). Only a correct answer to a shift trial pertaining to type 1 unambiguously signals successful attention shift[1]; efficiency of this shift is indexed by the RT. In this trial type, a difficulty in shifting attention from one category to the other is expected to yield a slower RT, since inhibition from the response category given on the previous trial is necessary. For example, when the question *Word*? was followed by the question *Male voice*? with the stimuli "beach" and "pear", respectively, both spoken by a female speaker (see example trials 6 and 7 in Table 3), the correct answers were "yes" and "no", respectively. If a participant had difficulties in shifting attention from one level (*Word*?) to the other (*Male voice*?), she may have been slower in inhibiting a "yes" response and answering "no" to the second question. Mean shift cost was obtained by subtracting the mean RT to no-shift-trials from the mean RT to shift-trials (type 1). There were 128 no-shift trials, and 40 type-1 shift trials for each participant. This task was administered in English.

2.2.2.3. Processing speed. We used the Speeded Naming task in the Language subset of the NEPSY-II (Korkman, Kirk, & Kemp, 2007). Participants named the sizes, colors, and shapes (e.g., *big red square*) of as many items as possible (out of 20) within 30 s. The task was

[1] There are two other trials types, which do not unambiguously indicate a difficulty in shifting attention, since a correct answer might also result from a lack of shifting (perseveration) from the *dimension*, or from the *answer* given on the previous trial. For example in a shift trial "male?" + "word?", if the first stimulus is "female/nonword" (no) and the next one is also "female/nonword" (no), any perseveration for the *answer* as well as for the *dimension* will yield a correct answer (no). These trials were not analyzed since correct answers may not indicate attention shift.

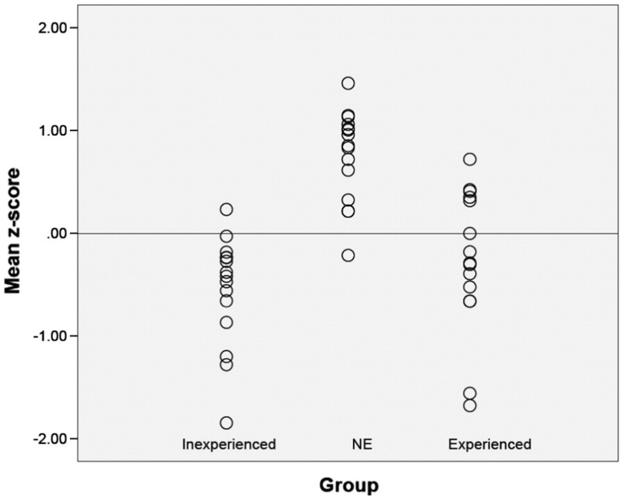

Fig. 2. Overall z-score (test conditions from all tasks) for each individual in each group (NE = Native English speakers).

administered in L1 (Korean). Three points were given for each fully named item (maximum scores: 60).

2.2.3. Lexical knowledge

Productive vocabulary knowledge, as an estimate of vocabulary size, was assessed using a picture naming task (Jared & Kroll, 2001). Sixty drawings from the Boston Naming Test (2nd edition, Kaplan, Goodglass, & Weintraub, 2001) were used in an E-Prime setup. Participants named each picture aloud as fast as possible. In total, 30 pictures increasing in difficulty were named in each language. Scoring was conservative and an error was counted if the expected name was not given (for example, "world" instead of "globe" was considered incorrect).[2] Naming latency (RT) was measured from the onset of the picture presentation until the onset of participants' oral response, for correct responses only. Naming RTs are interpreted as lexical retrieval speed in L1 or L2, respectively.

2.2.4. Phonological processing

We administered phonological processing tasks to measure three different domains of L2 phonological knowledge: segmental (task 1), suprasegmental (word stress) (task 2), and phonotactics (task 3). Tasks were administered in that order using E-prime.

2.2.4.1. Speeded segmental categorization with ABX. Participants were presented with pairs of non-words (A–B) in a male voice, followed by one member of the pair ('X', either A or B) in a female voice. They decided whether X sounded like A or like B by pressing one of two keys on a response box as quickly as possible (within 2500 ms). The stimuli consisted of 24 pairs of non-words, disyllabic CV(C)CVC, phonotactically legal in both Korean and English (see Supplement D). There were five test contrasts ([iː ɪ]; [uː ʊ]; [æ ɛ]; [p f]; [ɹ l]), which are phonemic in English (L2) but not in Korean (L1), and two control contrasts existing in both languages ([i o]; [s t]). All contrasts were embedded in the first (stressed) syllable. After a practice session with feedback, four blocks of 24 randomized items were presented. We hypothesized that higher accuracy would reflect participants' ability to establish new L2 phonemic categories, limiting L1 influence in processing.

2.2.4.2. Rapid encoding of word stress with sequence repetition. This task was modeled after Dupoux, Peperkamp and Sebastián-Gallés (2001) and Dupoux, Sebastián-Gallés, Navarrete and Peperkamp (2008). Multiple instances of two non-word minimal pairs (*trígu*, *tíbu*; *míban*, *mibán*) were recorded by a male native speaker of American English (see Supplement E). The first pair differed in one phoneme (common to English and Korean, /g/–/b/; control condition), and the second in the placement of word stress (first vs. second syllable; test condition). For each minimal pair, the participants first learned to associate the two items with two number keys, [1] or [2] (with feedback). Then, three experimental blocks were presented, each containing eight different sequences of the two non-words (sequences of two, four, and five non-words, respectively, e.g., *tígu tíbu tíbu tígu tíbu*). After a prompt, the participants had to reproduce each sequence by typing the associated keys in the correct order (e.g., 12212). Since the task was not speeded, only accuracy was measured. Responses were coded as correct only when the reproduced sequence was 100% correct. Since word stress is not part of the Korean phonological system, the Korean participants were expected to have difficulties encoding it in short-term memory even though they are able to perceive it (Altmann, 2006). We hypothesized that performance on longer sequences would reflect participants' ability to quickly recode an acoustic dimension into an abstract (phonological) format in order to maintain it long enough to reproduce the sequence.

2.2.4.3. Phonotactics and onset clusters with a speeded lexical decision. Participants were instructed to rapidly decide if the stimuli presented were English words or not by pressing "yes" or "no" on a response box. The test stimuli consisted of 33 English non-words; based on 33 English words containing an obstruent-liquid onset cluster (e.g., *proud*), we generated non-words by either inserting a vowel (similar to [ə]) in the cluster (e.g., [pʊˈɹaᵘd]) (u-set test condition, see Supplement F) or by inserting [ɪ] (e.g., [pɪˈɹaᵘd]) (i-set control condition), which is not epenthesized in that environment. One hundred thirty additional word and non-word items formed the baseline (control) condition. A trial started with the presentation of a fixation sign followed by the auditory stimulus. Stimuli presentation order was randomized. The next

Table 5
Pearson r coefficients and *p*-values (2-tailed) for test conditions in the phonological tasks.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)
Stress (SR)	r	.066		
	Sig.	.749		
	N	*26*		
Phonotactics (LD)	r	.214	.249	
	Sig.	.305	.202	
	N	*25*	*28*	
Phonological score (overall z–score)	r	.556**	.774**	.727**
	Sig.	.003	.000	.000
	N	*26*	*29*	*29*

Note: SR = sequence repetition; LD = lexical decision

Table 6a
Summary of descriptive statistics for the working memory tasks in L1.

		N	Mean	SD	Min.	Max.	CI (95%)
Digit forward + backward L1 (max.: 208)	Inexp.	15	82.2	23.9	36	146	13.25
	Experienced	15	101.3	27.3	68	153	15.10
	NE	15	79.1	29.8	38	147	16.50
Non-word forward + backward L1 (max.: 208)	Inexp.	15	31.1	12.1	15	62	6.68
	Experienced	15	29.5	10.6	14	46	5.88
	NE	15	21.1	16.3	10	76	9.01
Complex span sentence recall L1 (max.: 54)	Inexp.	15	31.8	6.2	25	44	3.45
	Experienced	15	30.9	7.1	22	44	3.92
	NE	15	41.7	6.1	30	52	3.39

Note: Inexp. = Inexperienced learners; Experienced = Experienced learners; NE = Native English speakers; SD = standard deviation; CI = confidence interval.

[2] The maximum score was 30 for English. However, the maximum score was 26 for Korean: 4 words were eliminated from the analyses due to a high number of uncertainty errors as to the identity of the drawing.

Table 6b
Pearson r coefficients and *p*-values (1-tailed) for working memory tasks and z-scores.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)	Phonological score
Digits	r	.021	.188	−.069	.139
	Sig.	.459	.164	.362	.232
	N	26	29	29	30
	FDR	.050	.029	.046	.033
Non-words	r	.306	.236	.082	.284
	Sig.	.064	.109	.337	.064
	N	26	29	29	30
	FDR	.013	.021	.042	.013
Sentence recall	r	.215	.494**	.091	.375
	Sig.	.146	.003	.319	.021
	N	26	29	29	30
	FDR	.025	.004	.038	.008

Note: SR = sequence repetition; LD = lexical decision; FDR = adjusted significance threshold according to the False Discovery Rate procedure (see Section 3.3 for details).

Table 7a
Summary of descriptive statistics for the working memory tasks in L2.

		N	Mean	SD	Min.	Max.	CI (95%)
Digit forward + backward L2 (max.: 208)	Inexp.	15	52.9	25.8	24	100	14.30
	Experienced	15	65.4	24.1	28	126	13.34
Non-word forward + backward L2 (max.: 208)	Inexp.	15	19.1	9.2	3	34	5.09
	Experienced	15	17.5	7.0	3	35	3.90
Complex span sentence recall L2 (max.: 54)	Inexp.	15	30.1	10.7	13	49	5.91
	Experienced	15	28.9	11.2	11	47	6.23
Paired associates L2[a](max.: 36)	Inexp.	15	18.3	5.7	9	26	3.15
	Experienced	15	20.5	7.9	6	30	4.35

Note: Inexp. = Inexperienced learners; Experienced = Experienced learners; SD = standard deviation; CI = confidence interval.
[a] We verified on the word/word condition that every participant's performance on this control condition was acceptable (average correct 5 out of 6), and therefore, the results from Block 1 are not reported here.

trial began after a response had been made, or after 3000 ms. Accuracy and RT were measured.

Learners of L2-English whose L1 does not allow obstruent-liquid onset clusters (such as Korean) often perceptually "repair" such clusters by inserting an epenthetic vowel (Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Kabak & Idsardi, 2007). Accordingly, learners may also lexically encode onset-cluster words with a vowel (e.g., *proud* might be perceived and encoded as *p[⍰]roud*). Learners who have not overcome perceptual epenthesis thus might detect non-words containing [ʊ] as real words (false-alarm). A correct rejection of [pʊˈɹaᵘd] as word would reflect learners' target-like lexical encoding of *proud* without an epenthetic vowel. The i-set non-words were to verify whether any (non-epenthetic) vowel could produce false alarms.

3. Results

3.1. Comparison across tasks

Comparing performance on different tasks that tap different types of phonological knowledge could mask the reasons for lower performance in a certain task, because the phonological processing on one task could be more challenging, but also because the task itself could be more difficult (see Sebastián-Gallés, 2005; but Dupoux et al., 2008). Ideally, the same tasks performed in both L1 and L2 would allow using L1 performance as a baseline to evaluate L2 performance. The control conditions used in our tasks (common contrasts for ABX, phonemic sequences for sequence repetition [SR], and baseline items in lexical decision [LD]; see each task description for details) are not fully comparable to an L1-baseline, but since the contrasts used in the control conditions for each task are, by definition, not conflicting with the respective L1 grammar of our participants, it can be considered a baseline to compare task demand across tasks. Crucially, if task demand is comparable across tasks, groups should behave similarly across tasks on this condition; therefore, no interaction between task and group is expected.

One subject performed below 2.5 SD of the mean accuracy on the control conditions for two out of three tasks and was therefore excluded from the analyses. To normalize for a potential difference in task demand across tasks, we computed a z-score for each participant for each task (see Fig. 1), using the mean and standard deviation of the entire sample (N = 45).

A linear mixed-effects model on the z-scores was fitted to examine the fixed effects of *task* (ABX, LD, SR) and *group* (Inexperienced, NE, Experienced) with *condition* and *task* as within-subject repeated effects.[3] There was no significant effect of *task*, $F(2, 81.8) = .14$, $p = 0.87$; The main effect of *group* was significant, $F(2, 41.3) = 7.6$, $p = 0.002$, and crucially, there was no significant interaction between the two factors, $F(4, 81.8) = .49$, $p = 0.74$, suggesting that the difference between groups was not modulated by task for this condition.

We conclude from this analysis that the differences observed between groups and tasks on the test conditions (Table 4) are not uniquely explicable from different task demands across tasks. In the following section, we proceed to analyze individual z-scores on each task as they relate to the cognitive measures we have obtained.

3.2. Phonological tasks

Participants' performance on each task was analyzed individually. In both learner groups, individual performance varied widely and sometimes overlapped. Some inexperienced participants had a performance equal to or higher than the average performance of the Experienced group, or vice-versa. An overall z-score was computed for each participant by averaging across the z-scores obtained for the test condition on each task to examine the effects for phonological development. Those who performed below 2.5 SD from the mean on the control condition for one task were considered outliers, and their test z-scores for that task were not included in the overall mean. This was the case for a total of 5 participants (ABX = 3; SR = 1; LD = 1). In addition, data from another participant for ABX were lost due to experimenter error. Table 4 presents an overview of each group's performance in the phonological tasks, and Fig. 2 presents individual overall phonological scores for each group.

A one-way ANOVA comparing phonological scores indicated that the three groups differed significantly, $F(2, 42) = 22.1$, $p < 0.001$, an effect driven by the native speakers' score which was significantly higher than both learner groups' (both $p < 0.001$). For the learners, phonological scores did not differ from one another, $p = 0.42$.

There was no correlation among the three tasks on the test condition, reflecting the fact that one learner whose performance was highly accurate on one task did not automatically obtain high accuracy on another task (Table 5).[4] Expectedly, the phonological score correlated with the z-scores on all three tasks.

3.3. Cognitive tasks

RTs in the processing tasks were trimmed (cutoff at 2 SD from the mean) to remove extreme responses. Averages were computed over correct responses only (for naming and attention). For each task, individual averages were computed based on the scoring procedures described above. Significance tests were adjusted for multiple comparisons using

[3] In SPSS 21, this model uses repeated effects within each subject (with compound symmetry correlation structure within subject) in a way that is equivalent to declaring subjects as random effects.

[4] In this and all following correlation tables, to facilitate reading, we highlighted correlations at $p < 0.01$ with dark gray cells, and correlations at $p < 0.05$ with light gray cells.

Table 7b
Pearson r coefficients and p-values (1-tailed) for L2 working memory tasks and z-scores.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)	Phonological score
Digits	r	.278	.523**	.008	.438**
	Sig.	.085	.002	.483	.008
	N	26	29	29	30
	FDR	.028	.003	.050	.013
Non-words	r	.446**	.219	.156	.397**
	Sig.	.011	.127	.209	.015
	N	26	29	29	30
	FDR	.019	.034	.041	.019
Sentence recall	r	.402**	.474**	.226	.504**
	Sig.	.021	.005	.119	.002
	N	26	29	29	30
	FDR	.022	.009	.031	.003
Paired associates	r	.149	.272	−.064	.172
	Sig.	.233	.077	.372	.182
	N	26	29	29	30
	FDR	.044	.025	.047	.038

Note: SR = sequence repetition; LD = lexical decision; FDR = adjusted significance threshold according to the False Discovery Rate procedure (see Section 3.3 for details).

Benjamini & Hochberg's False Discovery Rate procedure, at the 0.05 level (Benjamini & Hochberg, 1995). Only p-values that are *below* the adjusted FDR significance threshold are therefore significant and marked as such (**) in the tables.

3.3.1. Working memory

We hypothesized that individuals with a larger storage capacity (or a better span) and/or a better quality will show more robust phonological representations in the L2, which might effectively result in reduced influence from the L1 during processing, and hence in more native-like performance on our phonological processing tasks.

In addition, higher functioning complex span may facilitate processing of rapid spoken input, freeing resources that could improve phonological processing. Tables 6a and 6b present the results on L1 working memory tasks.

Table 8a
Summary of descriptive statistics for the attention control task (in L2).

		N	Mean	SD	Min.	Max.	CI (95%)
No-shift trials (% correct)	Inexp.	15	.78	.11	.49	.91	0.06
	Experienced	15	.84	.05	.75	.92	0.03
	NE	15	.93	.03	.86	.97	0.02
Shift trials (% correct)	Inexp.	15	.73	.12	.50	.88	0.07
	Experienced	15	.81	.08	.63	1.00	0.05
	NE	15	.90	.07	.75	1.00	0.04
No-shift trials, RT (ms)	Inexp.	15	877	208.5	456	1360	115.5
	Experienced	15	782	141.4	587	1034	78.3
	NE	15	884	120.2	715	1095	66.5
Shift trials, RT (ms)	Inexp.	15	917	190.2	564	1268	105.3
	Experienced	15	873	183.9	635	1210	101.8
	NE	15	947	148.0	716	1182	82.0
Shift cost	Inexp.	15	40.2	91.8	−159.4	128.5	50.9
	Experienced	15	91.2	87.8	−54.1	239.9	48.6
	NE	15	63.2	60.8	−61.2	179.7	33.7
CV no-shift	Inexp.	15	0.40	0.10	0.24	0.58	0.05
	Experienced	15	0.44	0.07	0.30	0.59	0.039
	NE	15	0.36	0.06	0.27	0.47	0.03
CV shift	Inexp.	15	0.38	0.10	0.25	0.62	0.05
	Experienced	15	0.42	0.09	0.26	0.58	0.050
	NE	15	0.34	0.07	0.21	0.43	0.04
CV shift cost	Inexp.	15	−0.01	0.10	−0.21	0.19	0.06
	Experienced	15	−0.02	0.08	−0.22	0.13	0.047
	NE	15	−0.02	0.05	−0.08	0.05	0.02

Table 8b
Pearson r coefficients and p-values (1-tailed) for the attention control task and z-scores.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)	Phonological score
No-shift trials (RT)	r	−.103	−.395	−.344	−.459
	Sig.	.308	.017	.034	.005
	N	26	29	29	30
	FDR	.042	.008	.013	.004
Shift trials (RT)	r	−.088	−.244	−.254	−.333
	Sig.	.335	.101	.092	.036
	N	26	29	29	30
	FDR	.046	.025	.021	.017
Attention shift cost	r	.013	.207	.188	.237
	Sig.	.475	.141	.165	.104
	N	26	29	29	30
	FDR	.050	.033	.038	.029

Note: SR = sequence repetition; LD = lexical decision; FDR = adjusted significance threshold according to the False Discovery Rate procedure (see Section 3.3 for details).

As shown in Table 6b, working memory measures in L1 do not strongly correlate with the phonological measures, except for complex span (sentence recall), which is significantly related to performance on the word stress sequence repetition task (see also Christiner & Reiterer, 2013, who find correlations with a Hindi imitation task). Also note that there is a correlational trend with the overall phonological score. Tables 7a and 7b present the same analysis for our L2 working memory tasks.

The phonological score is positively related to measures of digit span (storage capacity) and sentence recall (complex span), but not to our measure of L2 storage quality (paired associates). A higher storage capacity thus appears to be related to L2 phonological development. Our complex span measure in L2 correlates rather strongly with the overall phonological score.

3.3.2. Attention control

We hypothesized that more efficient attention control might aid in L2 phonological learning by allowing learners to focus on relevant linguistic or phonetic dimensions, resulting in a more precise processing of the speech signal. Tables 8a and 8b present the results for the attention control task.

As Table 8b shows, after FDR correction of significance thresholds, none of the RT or attentional shift cost measure (RT[shift]– RT[no-shift]) correlated significantly with the phonological scores, suggesting perhaps that a simple difference score might not be sufficient to uncover the potential relationship between attention control and phonological processing. Following Segalowitz and Frenkiel-Fishman (2005), we computed a coefficient of variation (CV) for the shift and no-shift measures (see Table 8a) and also examined correlations with accuracy scores. However, no significant correlation emerged from these measures with the phonological score.

3.3.3. Processing speed

We hypothesized that faster processing would free resources for handling incoming speech material, which could be critical for L2 phonological learning (Table 9a).

In our processing speed task, naming accuracy was significantly related to more accurate performance in the processing of word stress only (Table 9b).

Table 9a
Summary of descriptive statistics for the processing speed task in L1.

		N	Mean	SD	Min.	Max.	CI (95%)
Processing speed (max.: 60)	Inexp.	15	42.8	6.8	35	60	3.78
	Experienced	15	45.6	9.8	28	60	5.43

Note: Inexp. = Inexperienced learners; Experienced = Experienced learners; SD = standard deviation; CI = confidence interval.

Table 9b
Pearson r coefficients and *p*-values (1-tailed) for processing speed and z-scores.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)	Phonological score
Processing speed	*r*	.370	.427**	.023	.317
	Sig.	.032	.011	.453	.044
	N	26	29	29	30
	FDR	.025	.013	.050	.038

Note: SR = sequence repetition; LD = lexical decision; FDR = adjusted significance threshold according to the False Discovery Rate procedure (see Section 3.3 for details).

3.3.4. Lexical knowledge

We hypothesized a relationship between lexical knowledge and phonological processing because a larger vocabulary—especially in L2—might lead to a more efficient abstraction of phonological regularities across a larger number of words, which in turn could help process phonologically unfamiliar L2 speech forms. For the purpose of interpreting the role of L1 vocabulary size in L2 phonological processing, it is important to note that for the learners, productive knowledge (accuracy) in L1 and L2 were significantly correlated ($r = .430$, $p = 0.009$), as were retrieval RTs in L1 and L2 ($r = .557$, $p < 0.001$). Tables 10a and 10b give a summary of the results for L1 lexical knowledge, and Tables 11a and 11b for L2.

We observed some moderate negative correlations with speed of L1 lexical retrieval (e.g., the faster the L1 naming RT, the higher the phonological score), but after FDR correction, no correlation was significant, suggesting that if vocabulary size in L1 helps process L2 phonological input, this relationship was not strong in our data.

L2 naming accuracy also moderately correlated (positively) with phonological scores, suggesting that a larger vocabulary in L2 might be linked to phonological development. However, FDR correction reveals that no correlation was significant, indicating that if L2 vocabulary size helps process L2 input as has been argued previously (see Bundgaard-Nielsen et al., 2011; Majerus et al., 2008), the relationship is not very strong in our case, and did not relate to segmental perception.

3.3.5. Other measures

We also performed analyses of the phonological score with the executive function assessment done using the BRIEF-A questionnaire, and the demographic background variables. None of these variables was correlated with the phonological score after FDR correction.

4. General discussion and conclusion

We set out to explore potential links between cognitive abilities and individual differences in L2 *phonological* processing. Individual differences in phonological processing were measured in perception tasks targeting three phonological dimensions. Participants also took part in a battery of tests designed to measure three cognitive abilities (i.e., working memory, attention control, processing speed) and lexical knowledge in both L1 and L2. Background variables were recorded to evaluate their relationship with the overall phonological score.

Our findings contribute to clarify the relationship of these four areas to L2 phonological processing specifically: Our data mirror previous evidence that working memory is related to phonological processing (e.g., L2 vowel discrimination, Aliaga-Garcia et al., 2011), but we used a wider array of working memory tasks. Our results also extend this observation to other dimensions of phonological processing (e.g., consonants, or suprasegmentals). Our findings show that among the various working memory measures in L1 and L2, the L2 complex span seems to be most strongly related to the overall phonological score. While it is beyond the scope of the present paper to extensively explore the respective contributions of the different cognitive variables to phonological processing scores, the three strongest significant correlations that we obtained involved L2 working memory: L2 complex span ($r = .504$), and L2 storage capacity (digits, $r = .438$; non-words, $r = .397$). Fig. 3 graphically displays this relationship between L2 complex span (sentence recall) and phonological score.

However, one measure of L2 working memory, storage quality (paired associates), was not related to our phonological measures. The reasons for this are unclear and might be related to the specific tasks we used. Other studies have used different methods to examine the precision of phonological storage, such as serial non-word recognition tasks (Gathercole, Pickering, Hall, & Peaker, 2001; O'Brien, Segalowitz, Freed, & Collentine, 2007). Since recognition tasks are typically free of articulatory confounds, performance might be more directly related to phonological processing (see also Aliaga-Garcia et al., 2011). We also hypothesized that attention control, processing speed, and lexical knowledge might be related to individual differences in phonological processing. These predictions were not clearly upheld in correlational analyses, again perhaps because of the kind of tasks used, which might not allow uncovering potential relationships. A word of caution is in order here. Our analysis mostly examined correlations, therefore leaving the examination of more specific causality relationships between phonological development and cognitive abilities for future studies.

The conspicuous lack of correlation between our phonological score and any of the demographic variables suggests that the large individual differences in phonological processing we observed at the individual level cannot be readily explained by such factors within each group.

Table 10b
Pearson r coefficients and *p*-values (1-tailed) for L1 lexical knowledge tasks and z-scores.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)	Phonological score
Accuracy	*r*	.309	.138	.197	.282
	Sig.	.062	.238	.152	.066
	N	26	29	29	30
	FDR	.019	.044	.031	.025
RT	*r*	.086	−.170	−.420	−.317
	Sig.	.338	.189	.012	.044
	N	26	29	29	30
	FDR	.050	.038	.006	.013

Note: SR = sequence repetition; LD = lexical decision; FDR = adjusted significance threshold according to the False Discovery Rate procedure (see Section 3.3 for details).

Table 10a
Summary of descriptive statistics for the lexical knowledge tasks in L1.

		N	Mean	SD	Min.	Max.	CI (95%)
Productive knowledge L1 (accuracy)	Inexp.	15	0.82	0.06	0.73	0.96	0.03
	Experienced	15	0.81	0.07	0.65	0.89	0.04
	NE	15	0.93	0.11	0.53	1.00	0.06
Retrieval RT L1 (ms)	Inexp.	15	1313	208	1002	1792	115.1
	Experienced	15	1393	347	870	2201	191.9
	NE	15	1072	160	912	1355	88.39

Note: Inexp. = Inexperienced learners; Experienced = Experienced learners; NE = Native English speakers; SD = standard deviation; CI = confidence interval.

Table 11a
Summary of descriptive statistics for the L2 lexical knowledge tasks.

		N	Mean	SD	Min.	Max.	CI (95%)
Productive knowledge L2 (accuracy)	Inexp.	15	0.50	0.15	0.27	0.77	0.08
	Experienced	15	0.60	0.11	0.37	0.77	0.06
Retrieval RT L2 (ms)	Inexp.	15	2127	419	1608	2872	232.0
	Experienced	15	2378	604	1647	3352	334.6

Note: Inexp. = Inexperienced learners; Experienced = Experienced learners; SD = standard deviation; CI = confidence interval.

Table 11b
Pearson r coefficients and *p*-values (1-tailed) for L2 lexical knowledge tasks and z-scores.

		Segmentals (ABX)	Stress (SR)	Phonotactics (LD)	Phonological score
Accuracy	*r*	.305	.257	.164	.328
	Sig.	.065	.089	.197	.038
	N	26	29	29	30
	FDR	.019	.025	.031	.006
RT	*r*	−.059	.134	−.318	−.099
	Sig.	.388	.244	.047	.301
	N	26	29	29	30
	FDR	.050	.038	.013	.044

Note: SR = sequence repetition; LD = lexical decision; FDR = adjusted significance threshold according to the False Discovery Rate procedure (see Section 3.3 for details).

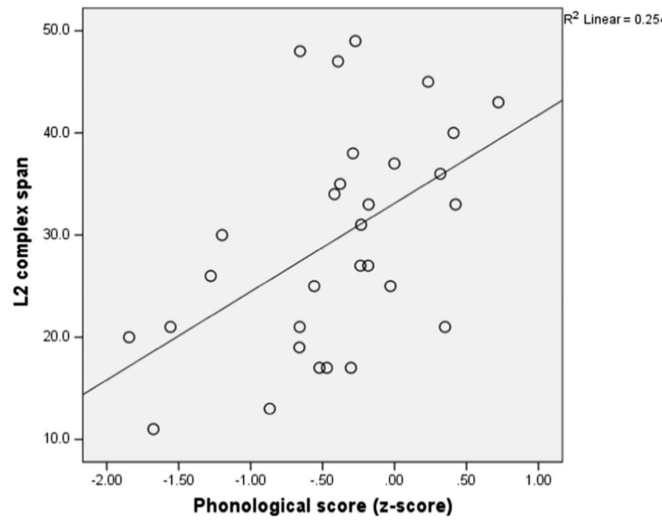

Fig. 3. Scatterplot of the relationship between L2 complex span and phonological score for the 30 Korean learners in our sample.

LOR and age of arrival, for example, did not correlate with individual performance on phonological processing tasks. The observed lack of consistency in performance among individuals (see Table 5) is also in line with the suggestion that LOR (which was constant for each person in all tasks) may not be the principal determinant of performance in our phonological tasks.

Overall, our results contribute to show that the relationship between cognitive abilities and L2 phonological processing can be conceived of as potentially impacting the entire phonological system—at least several dimensions including segmentals, word stress, and phonotactics. Of course, our results do not mean that the cognitive abilities which correlate with phonological scores, such as L2 complex span, are uniquely related to phonological processing. Rather, cognitive abilities across these three core areas can also play a role for L2 phonological development.

Interestingly, there was not one single cognitive variable with which all three phonological tasks and the overall phonological score would correlate. Instead, some phonological domains seem to be related with certain cognitive abilities more than other domains. What this suggests at first is that phonological processing is a complex task, requiring recruitment of various cognitive abilities.

However, a caveat to that interpretation is that the different tasks in our study—despite being comparable in task demand—are likely drawing on different types of cognitive abilities necessary for their completion, in addition to the phonological knowledge needed. For example, it is clear that the sequence repetition task will necessitate recruiting working memory directly and perhaps to a larger extent than the lexical decision task. To what extent the task characteristics themselves are obliterating the contribution of phonological knowledge is unclear, but future studies would benefit from controlling for this possibility in a much stricter way than we did. A novel aspect of this study is the attempt to obtain an individual measure of L2 phonological processing efficiency (our *overall phonological score*) from three different areas of phonology, and to relate these to individual differences in cognitive abilities. While such a global phonological score likely needs to be refined in future studies, we hope that it could be used as a valid measure of the global phonological processing ability of a learner, independently of production-based measures such as foreign-accentedness ratings.

In light of our results, the question arises as to the nature of the interplay between cognitive abilities and phonological processing. If a more efficient L2 working memory, such as complex span for example, is linked to more accurate and/or less L1-based phonological processing of L2 input, we need to gain a more precise understanding of the mechanism behind this relationship. In the Introduction, we mentioned that the generally assumed mechanism through which cognitive functioning might influence L2 development is that higher cognitive performance enhances the quality of the input (Segalowitz, Gatbonton, & Trofimovich, 2009): for example, it might promote more accurate perception or allow learners more time to process the input by having longer access to it. We hypothesize that a crucial aspect of more native-like L2 phonological processing lies in reduced interference from the L1, and automatization of processing for L2-specific phonological dimensions (Segalowitz, 2010). It is crucial to work towards defining specific mechanisms through which various cognitive abilities could reduce this L1 interference and impact L2 phonological development, as well as teasing apart these various possibilities.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lindif.2015.04.005.

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