Title:
Domain-General Auditory Processing Partially Explains Second Language Speech Learning in Classroom Settings: A Review and Generalization Study

RUNNING HEAD:
AUDITORY PROCESSING & L2 SPEECH

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Abstract

To date, a growing number of studies have shown that domain-general auditory processing, which prior work has linked to L1 acquisition, could explain various dimensions of *naturalistic* L2 speech proficiency. The current study examined the generalizability of this topic to L2 speech learning in *classroom* settings. The spontaneous speech samples of English-as-a-Foreign-Language learners were analyzed for the fluent and accurate use of pronunciation and lexicogrammar, and linked to a range of their auditory processing profiles. The results identified moderate-to-strong correlations between the participants' accurate use of lexicogrammar and audio-motor sequence integration scores (i.e., the ability to reproduce melodic/rhythmic information). However, the relationship between phonological proficiency and auditory acuity (i.e., the ability to encode acoustic details of sounds) was non-significant. While the findings support the audition-acquisition link to classroom L2 speech

learning to some degree, they only suggest that this link is robust for the acquisition of lexicogrammar information.

Key words: Second language speech; Pronunciation; Auditory Processing; Foreign language learning

It is widely understood that adult second language (L2) speech learning is subject to a great deal of individual variation. While some learners are able to achieve high-level L2 proficiency with apparent ease, others experience a tremendous amount of difficulty reaching the same state (e.g., Abrahamsson & Hyltenstam, 2009). One explanation for this variation is how much exposure learners currently have and have previously had to the target language. This corresponds to a usage-based perspective to L2 learning, which views proficiency in terms of how much (quantity), in what way (quality) and how recently (timing) learners have practiced the target language (Ellis, 2006). An interesting testing ground for experience effects is the foreign language setting, where exposure to L2 input is limited to several hours of language-focused instruction per week (Muñoz, 2014). There is ample evidence that the outcomes of classroom L2 speech learning could be influenced by factors such as the length of foreign languageducation (Jaekel, Schurig, Florian, & Ritter, 2017), extra-curricular activities (e.g., Muñoz, 2014), type of instruction (e.g., Norris & Ortega, 2000 for focus on form vs. focus on formS), and timing of learning (e.g., Larson-Hall, 2008 for early vs. late starters).

At the same time, it has been reported that experience-related factors alone cannot fully explain the variance in foreign language learning success (e.g., Saito & Hanzawa, 2016 for approximately 15-20% of variance accounted for by the length, type and timing of L2 experience). Even if two individuals of the same age and with similar levels of motivation engage in the same type of practice for the same period of time, they will most likely end up with different levels of proficiency (Doughty, 2019). Part of this variation can be attributed to learner-internal abilities related to perception and general cognition (e.g., Linck et al., 2013 for working memory). These are thought to be instrumental to the acquisition of relatively difficult, complex and non-salient linguistic features, as they can help learners better encode, analyze, memorize and internalize the input they receive (Li, 2016). In this paper, we elaborate on one such ability widely cited in the first language (L1) acquisition literature which acts as a foundation of human language and music learning: *domain-general* auditory processing. The goal of this paper is to examine the generalizability of this framework to L2 speech learning in the instructed foreign language setting.

Background

Domain-General Auditory Processing and First Language Acquisition

Research on individual differences in L1 acquisition has mainly investigated two sets of processes: (a) those aspects of neurocognitive functioning specifically devoted to language acquisition (Campbell & Tyler, 2018); and (b) those that can be characterized as domain-general learning mechanisms (e.g., Hamrick, Lum, & Ullman, 2018 for declarative vs. procedural memory). One well-researched domain-general construct is auditory processing, defined as the ability to precisely represent and remember characteristics of sounds (Mueller, Friederici, & Männel, 2012; Tierney & Kraus, 2014; Tierney, White-Schwoch, MacLean, & Kraus, 2017).

Auditory processing essentially comprises two dimensions. The first relates to the type of audio signal that is processed —i.e., temporal vs. spectral (Zatorre & Belin, 2001; Flinker, Doyle, Mehta, Devinsky, & Poeppel, 2019). Temporal processing is defined as one's capacity to track changes in amplitude over time. This ability is integral to a range of phenomena related to fluency (e.g., phonation time, pause frequency) and segmental contrasts (e.g., short vs. long vowels), prosody (e.g., durational differences in weak vs. strong vowels, voice onset time), and rhythm (e.g., duration between two syllables, stressed syllables vs. morae). Spectral processing is defined as one's capacity to track changes in the frequency content of the signal, such as pitch (the frequency of vocal cord vibration) and formants (the energy concentration at different frequency bands). This ability is fundamental to the correct assignment of stress and intonation (e.g., lexical tones in Mandarin), the fine-tuning to isochrony (e.g., syllable, stressed vs. mora-timed), and the refinement of segmental accuracy (e.g., third formant variability for English [r] and [l]).

The second dimension relates to the type of information processing involved, e.g., audio-motor integration (i.e., proceduralizing temporal and spectral patterns) vs. auditory acuity (encoding temporal and spectral *details* of sounds). In the early stages of L1 acquisition, infants need to not only detect and remember novel sound patterns and contrasts, but also must consolidate and make them available for motor action (reproduction) (Flaugnacco et al., 2014; Tierney & Kraus, 2014). At the same time, auditory acuity ability is needed to detect subtle differences in the temporal and spectral aspects of acoustic signals at a fine-grained level. Fine auditory acuity thus makes possible phonetic restructuring which will in turn help learners increase the sophistication of their auditory representations, and by extension to attain more advanced linguistic proficiency (McArthur & Bishop, 2005). The constructs of the auditory processing model and corresponding measures used in the current study are summarized in the first two columns in Table 1.

Table 1

Constructs of Auditory Processing

Type of audio information	Type of information processing	Measures[a]

Temporal	Audio-motor integration	Rhythm reproduction
	Auditory acuity	Duration discrimination
Spectral	Audio-motor integration	Melody reproduction
	Auditory acuity	Pitch discrimination
		Formant discrimination

Note. [a]The measures will be detailed in the Methods.

Whereas auditory acuity develops and reaches its peak around 7-10 years of age, the degree of precision gradually declines with age (Skoe, Krizman, Anderson, & Kraus, 2015). Comparatively, auditory-motor integration continues to improve until the late 20's, and is followed by a great amount of individual variation over the remainder of the lifespan (Thomson, White-Schwoch, Tierney, & Kraus, 2015). Auditory processing is fundamental to every stage of L1 acquisition. Within the first six to eight months of life, for example, infants use temporal and spectral information in speech to distinguish between the probabilities of individual phonemes existing in L1 phonetic inventories (Kuhl, 2000). At the same time, both temporal and spectral processing are used to identify word boundaries (Cutler & Butterfield, 1992), track syntactic structure (Marslen-Wilson et al., 1992) and detect morphosyntactic cues (the identification of suffixes) (Joanisse & Seidenberg, 1998). This eventually enables L1 learners to attend to the temporal and spectral details of sounds and words, and hence perceive and produce a number of phonologically similar words with correct morphological markers (Gervain & Werker, 2008). Deficits in auditry processing are known to result in a range of global language problems. For example, the audition profiles of L1 learners widely vary between normal and delayed L1 acquirers (Surprenant & Watson, 2001). Furthermore, individual differences in auditory processing have been linked to L1 learning difficulty (Goswami, Wang, Cruz, Fosker, Mead, & Huss, 2011). In spite of this large body of evidence, the causal nature of the link between auditory processing and L1 acquisition continues to be debated (cf., Halliday & Bishop, 2006; Rosen & Manganari 2001; Snowling, Gooch, McArthur, & Hulme, 2018).

Domain-General Auditory Processing and Second Language Acquisition

To test the domain-generality of auditory processing, a growing number of scholars have begun to examine the extent to which the construct explains success in post-pubertal speech L2 learning (for a comprehensive summary, see Table 2). Within the paradigm of novel word learning, there is some evidence that learners with more precise auditory acuity and integration abilities can better perceive foreign sound patterns and contrasts that they have never learned (e.g., Kempe, Bublitz, & Brooks, 2015 for L1 English speakers' perception of Norwegian pitch and vowel contrasts). Furthermore, auditory processing has been shown to predict gains in perception and production following focused training on novel and/or foreign sounds and words (e.g.,

Wong & Perrachione, 2007 for pseudo words; Li & DeKeyser, 2017 for real Chinese words). In particular, the latter training studies provide ample implications. Given that the studies directly tracked how participants with different auditory profiles reacted to short-term in-laboratory training, the findings present *longitudinal* evidence regarding precisely how auditory processing helps humans notice, process, and integrate a novel language when they encounter it for the first time. Notably, training studies of this kind allow researchers to discuss the longitudinal effects of auditory processing in the initial stage of language learning. However, the role of auditory processing in long-term second language learning in various contexts (immersion vs. classroom) is unclear, especially when it comes to acquisition of other forms of linguistic knowledge such as lexicogrammar.

Table 2

Summary of Studies Examining Auditory Processing and Novel Word Learning

Studies	Subjects	L2 tasks	Auditory measures	Findings
Wong & Perrachione (2007)	17 L1 English speakers	Learning 18 English pseudowords with Mandarin-like pitch patterns	Pitch identification (acuity)	Novel word learning success was tied to auditory processing (pitch acuity) and experience (prior music training).
Perrachione et al. (2011)	64 L1 English speakers	Learning 18 English pseudowords with Mandarin-like pitch patterns	Pitch identification (acuity)	Those with strong auditory processing benefitted from high-variability training. Those with weaker auditory processing benefited from low-variability training.
Cooper & Yang (2012)	28 L1 Thai & 26 L1 English speakers	Learning novel five Cantonese syllables with five different tones	Composite scores of pitch and rhythm discrimination (acuity)	Novel tone learning success was linked to composite pitch and rhythm discrimination especially among non-tonal (L1 English) speakers
Kempe et al. (2015)	118 L1 English speakers	Discriminating foreign phonological contrasts (Norwegian)	Pitch and formant discrimination (acuity)	Auditory processing mediated the relationship between music experience and novel sound perception.
Li & DeKeyser (2017)	41 L1 English speakers	Learning 16 real Chinese words	Melody reproduction (integration)	Those with more precise auditory processing demonstrated greater gains.

Though limited in number, some studies have explored the relationship between auditory processing and L2 phonological and morphosyntax learning, when participants have had *naturalistic*, *extensive* and *immersive* learning experience with a target language (for a summary, see Table 3). For example, in the context of 28 Greek L2 learners of English (with approximately 10 years of L2 learning experience), Legeris and Hazan (2010) found that auditory processing profiles were correlated with learning gains in L2 vowel accuracy, when they received four hours of training simulating the intensive and

highly-variable nature of naturalistic L2 speech learning (i.e., high variability phonetic training). More recently, the team at University of London has conducted a series of studies focusing on more than 300+ adult L2 learners with diverse L1, experience, auditory processing, and linguistic profiles (e.g., Kachlicka, Saito, & Tierney, 2019; Saito, Kachlicka, Sun, & Tierney, 2020). Broadly, these studies have shown phonological and grammatical proficiency are predicted by individual differences in integration and acuity, even after biographical factors (age, experience) are controlled for. Such auditory processing effects were stronger when the learners had practiced the L2 in *naturalistic* settings (> 1 year).

Table 3

Summary of Studies Examining Auditory Processing and Naturalistic L2 Learning

Studies	Subjects	L2 tasks	Auditory measures	Findings
Lengeris & Hazan (2011)	28 L1 Greek speakers	Learning L2 English vowel contrasts (perception)	Formant discrimination (acuity)	Those with more precise auditory processing demonstrated more advanced L2 speech proficiency (accuracy), when they received intensive/immersive speech training.
Kachlicka et al. (2019)	40 L1 Polish speakers	L2 English vowels (perception) L2 English grammaticality judgments	Spectral and temporal discrimination (acuity) and reproduction (integration)	Participants' L2 proficiency (accuracy) was equally determined by auditory processing and experience factors
Saito et al. (2020)	100 L1 Polish speakers	L2 English phonological accuracy and fluency (production)	Spectral and temporal discrimination (acuity) and reproduction (integration)	Auditory acuity was predictive of phonological accuracy attainment in particular. The link between auditory integration and fluency was minor at best.
Saito et al. (in press)	138 L1 Chinese, Polish, & Spanish speakers	L2 English vowel/prosody (perception) L2 English grammaticality judgements	Spectral and temporal discrimination (acuity)	Effects of auditory processing were clearly observed among relatively experienced L2 learners' accuracy performance (> 1 year of immersion).
Saito et al. (in press)	30 L1 Chinese speakers	L2 English vowel and prosody (production)	Spectral and temporal discrimination (acuity)	Those with more precise auditory processing demonstrated more learning during 8 months of immersion (accuracy but not fluency).
Sun et al. (in press)	50 L1 Chinese speakers	L2 English vowel and prosody (perception)	Spectral and temporal discrimination (acuity) and reproduction (integration)	Auditory processing was predictive of the amount of L2 suprasegmental learning (accuracy) over the course of 4 months of immersion.

To further extend this critical line of L2 research, the current study examines the generalizability of the relationship between auditory processing and various dimensions of L2 speech learning in *foreign language* classroom settings. According to Larson-Hall (2008, p. 36), foreign language classroom learning is a "minimal input" setting. Input exposure in these settings are limited to several hours of language-focused instruction per week, and opportunities to use the language outside of the classroom are rare. The rate of success in foreign language classrooms can be attributed not only to how much learners have practiced, but to how recently, meaningfully and interactively they have done so (Muñoz, 2014). Importantly, however, the final outcomes of classroom L2 learning are subject to a great deal of individual variation, even for students in the same classrooms with similar experience profiles (Saito & Hanzawa, 2016).

A well-researched source of this variation is foreign language aptitude—a set of perceptual and cognitive abilities that underlie the development of foreign language proficiency. Previous research has shown that certain abilities are instrumental to the acquisition of relatively difficult linguistic features within a short period of time, arguably because they help L2 learners better encode, analyze, memorize and internalize input at every opportunity (e.g., phonemic coding, grammar inferencing; see Skehan, 2016). While foreign language aptitude is found to predict various dimensions of classroom L2 learning (e.g., $r = .49$ in Li's meta-analysis, 2016), such aptitude construct has been operationalized as composite competence *specific* to foreign language learning, which comprises a combination of multiple skills (e.g., phonological awareness, analysis, and memory for phonemic coding). To further examine precisely what kinds of perceptual-cognitive abilities explain aptitude effects in L2 acquisition, a growing number of scholars have begun to test the predictive power of more fine-grained, domain-general cognitive abilities (e. g., Linck et al., 2013 for their attempts to include working memory as a part of foreign language aptitude). In line with this goal, the current investigation introduces an ability that represents a perceptual-cognitive foundation of human language learning: *domain-general* auditory processing (Tierney & Kraus, 2017). In doing so, we propose and provide evidence for a new framework of aptitude for L2 *speech* learning in reference to this ability.

Predictions: Auditory Processing, Experience, & Classroom L2 Speech Learning

In the current investigation, we set out to examine the relationships between auditory processing, experience, and L2 speech acquisition. To this end, the following research question is formulated:

- To what degree do auditory processing and experience factors predict the accuracy and fluency dimensions of L2 speech learning in the foreign classroom setting?

L2 speech learning is characterized as a "multifaceted phenomenon" which involves the development of accurate and fluent language in extemporaneous speaking (Révész Ekiert, & Torgersen, 2016; Trofimovich & Isaacs, 2012). Accuracy encompasses the ability to pronounce consonants and vowels without L1 substitutions (segmentals), correctly assign word and sentence stress (prosody), choose appropriate combinations of words in different contexts (vocabulary), and correctly mark tense, aspect, agreement, plurality and word order with suffixes (morphosyntax). Fluency entails the ability to deliver speech at an optimal rate (speed) without too many pauses (breakdown), repetitions, or self-corrections (repair). Experience refers to the extent to which learners have extensively and intensively studied a target language inside and outside classroom settings. Auditory processing is operationalized as the integration and acuity abilities of temporal and spectral information. Our predictions regarding the relationship between audition, experience, and L2 speech learning are two-fold in accordance with the different level of learning difficulty (accuracy > fluency).

Prediction 1: Experience factors could be a key determinant of the relatively easy aspects of L2 speech learning (temporal fluency)

We posit that most L2 learners will develop speaking fluency (speed and breakdown) regardless of individual differences in auditory processing (i.e., weak audition effects) as long as they have sufficient practice with the target language (i.e., clear experience effects). This is in line with emerging empirical findings showing that much improvement occurs in the fluency rather than accuracy aspects of language following short periods of L2 immersion (Mora & Valls-Ferrer, 2012) and classroom instruction (Saito & Hanzawa, 2018). In the context of L2 English speakers in Canada, Derwing and her colleagues conducted a series of longitudinal investigations, showing that the temporal characteristics of L2 speech (fluency) continue to improve as a function of increased input and conversational experience (e.g., Derwing, Munro, Thomson, & Rossiter, 2009); but that nativelike accuracy remains unchanged regardless of extensive immersion (Derwing & Munro, 2013 for perceived accentedness; Munro, Derwing, & Saito, 2013 for vowel accuracy). As shown in Table 3, the link between auditory processing and L2 fluency in naturalistic settings is non-significant (Saito et al., in press) or minor (Saito et al., 2020).

Prediction 2: Auditory processing factors determine the rate of success for the relatively difficult aspects of L2 speech learning (lexicogrammar and phonological accuracy)

Auditory processing may play a key role in determining learning success for the accuracy (rather than fluency) aspects of L2 speech learning (i.e., phonological and lexicogrammar accuracy). The development of accuracy is known to be relatively resistant to rapid change at both the phonological (Flege, 2016) and lexicogrammatical levels (Saito, 2019). Interestingly, whereas spoken lexicogrammar slowly, gradually, and continuously becomes more accurate after an extensive amount of experience (e.g., 3-5 years of immersion; Saito, 2015), high-level phonological refinement requires not only ample practice (e.g., 5+ years of immersion; Flege, Takagi, & Mann, 1995), but also special L2 learning aptitude profiles (e.g., high phonemic coding ability; Hu, Ackerman, Martin, Erb, Winkler, & Reiterer, 2013). As shown in Table 3, much evidence has suggested that

auditory acuity is predictive of L2 phonological and morphosyntax accuracy (e.g., Saito et al., in press). Thus, our hypothesis is that more precise auditory encoding and integration of spectral and temporal information underlies the successful acquisition of L2 phonological and lexicogrammar accuracy. To perceive and produce L2 segmental and suprasegmental contrasts, learners need to encode, analyze and integrate novel spectral and temporal patterns (Gervain & Werker, 2008). For lexicogrammar, precise spectral and temporal processing directly relates to the accurate perception of pitch height and contour. This directly helps learners establish lexical and syntactic boundaries while attending to perceptually non-salient morphosyntactic markers (Joanisse & Seidenberg, 1998; Leonard, 1994). Precise auditory processing may also facilitate the comprehension and production of collocations, which are fundamental to the L2 speech accuracy (Saito, 2020), and which are marked by shorter word duration (Gregory, Raymond, Bell, Fosler-Lussier, & Jurafsky, 1999).

The constructs, predictors, and outcome measures relevant to the auditory processing account of L2 speech acquisition are summarized in Table 4.

Table 4

Constructs of L2 Speech Proficiency and Its Predictors

Dimensions	Subcomponents	Levels of learning difficulty	Primary predictors	Measures
Accuracy	Phonology	Strong	Strong effects of auditory processing	Segmental and prosodic accuracy
	Lexicogrammar	Mid	Moderate effects of auditory processing	Weighted accuracy; collocation association
Fluency	Speed	Low	Experience effects	Articulation rate
	Breakdown		Experience effects	Pauses between and within clauses

Note. [a]The measures will be detailed in the Methods.

Method

Participants

The participants consisted of a total of 39 college students (7 males, 32 females) who majored in a wide range of social science and humanities programs at a large university in Vietnam (M_{age} = 20.1 years, *Range* = 18-21 years). Their proficiency based on TOEIC scores (measuring composite L2 English listening and reading proficiency) could be considered as ranging

from A1/2 (Basic Users) to B1/2 (Independent Users) (M = 512.9 out of 990, *Range* = 370-690). The results of the questionnaire showed that the participants had started learning L2 English at different ages ($M_{age\ of\ learning}$ = 9.0 years, *Range* = 8-11 years). They studied L2 English in classroom settings without any experience abroad ($M_{length\ of\ learning}$ = 1182.8 hours, *Range* = 637.5-2457.5 hours). At the time of the project, all the participants were registered for four hours of English classes per week. They reported that they spend a varied amount of time outside classrooms practicing the target language ($M_{extracurricular\ L2\ practice}$ = 9 hours, *Range* = 6-11 hours). Some participants attempted to have L2 conversation activities with other L1 and L2 English users (M = 0.7 hours, *Range* = 0-5 hours). For practical reasons, whereas we elicited each participant's L2 speech performance and EFL backgrounds on a face-to-face meeting, their auditory data were collected remotely (see below).

L2 Speaking Task

As a part of the EFL curriculum at the university, students' L2 English proficiency was evaluated from multiple angles. Each student participated in a face-to-face tutoring session with an instructor. Not only were students asked to demonstrate their L2 English proficiency through a variety of tasks, but they also received feedback and training from the instructor. The entire session took about one hour per participant. Among a set of activities in which the participants engaged, we report the results of their oral performance via a monologue task which they completed at the beginning of their tutoring session. The task format was chosen, because our pilot study showed that the task was suitable for eliciting sufficiently long L2 speech samples which can index the participants' extemporaneous use of a wide variety of lexicogrammatical features (see below). The participants were asked to talk about the following topic for four minutes: *What was the most recent favorite movie of yours that you watched?* To ensure that the participants would continue to speak for a sufficiently long time (fully four minutes), six discussion points were also prepared and presented below the main topic: (1) What was it called? (2) What kind of movie was it? (3) When and where did you watch it? (4) Who were the main characters? (5) What happened in the movie? and (6) Why did you like it? To avoid false starts, the talkers had to start their speech by using the following fixed first line: "*The favorite movie I recently watched was* _____." All the speech tokens were recorded in a quiet room with a Roland-05 audio recorder, set at 44.1 kHz sampling rate and 16-bit quantization, and a unidirectional condenser microphone. The audio data were transcribed for the lexicogrammar fluency and accuracy analyses (see below). While the number of words per token was substantially different for each participant (M = 174.0 words, *Range* = 130-240 words), the speech surpassed the suggested threshold for robust L2 vocabulary analyses (In'nami & Koizumi, 2013 for +100 words).

Fluency Measures

We assessed L2 fluency from the speech sample using two measures (see Table 4). In light of Tavakoli and Skehan's (2005) framework of utterance fluency, speech was analyzed as follows. First, speed fluency was assessed in terms of articulation rate, calculated by dividing the total number of syllables produced by phonation time. Phonation time was analyzed

by subtracting all the fillers (ah, oh, eh) and extensive silence (greater than 250 ms) from the total length of each sample. Second, pausing behavior was assessed in terms of the frequency of filled and unfilled pauses, calculated by dividing the number of pauses by the total number of words. As suggested in many L2 fluency studies (e.g., Lambert et al., 2016), breakdown fluency was calculated separately for pauses in the middle and end of clauses. The frequency of mid-clause pauses is assumed to represent the efficiency of L2 linguistic encoding processes, while the ratio of clause-final pauses is supposed to reflect conceptualization processes (Kormos, 2006). Two researchers separately transcribed 10 similar L2 speech samples (used in a different project), and coded them for speed, breakdown and repair fluency. Next, they had a meeting, where they checked the results of their transcripts and fluency analyses. Since there was no evidence of disagreement between the coders, one of them completed the transcription and fluency analyses of the main dataset (n = 39 Vietnamese EFL speakers' monologues).

Accuracy Measures

We assessed L2 accuracy from the speech sample using two measures (see Table 4). Traditionally, accuracy has been dichotomously analyzed by tallying the number of linguistic errors in obligatory contexts (correct vs. incorrect). More recently, however, many scholars have emphasized the notion of error gravity in L2 accuracy judgements (Derwing & Munro, 2015 for comprehensibility; Foster & Wigglesworth, 2016 for weighted accuracy; Saito, Trofimovich, & Isaacs, 2017 for segmental, prosodic and lexical appropriateness). According to this paradigm, there is consensus that certain errors have a greater negative impact on global L2 communicative adequacy than others (Révész et al., 2016); that the relative (rather than dichotomous) quality of accuracy should be evaluated from multiple angles via a combination of objective and subjective analyses (Isaacs & Trofimovich, 2012); and that phonological and lexicogrammar accuracy influence each other and thus should be analyzed separately (Corwther et al., 2015). Each dimension of accuracy was analyzed as follows.

Phonological Accuracy. We adopted the training and rating procedure for subjective analyses of phonological accuracy originally conceptualized, developed and validated in Saito et al. (2017). First, two linguistically trained raters were recruited: L1 Vietnamese speakers with high-level L2 English proficiency. Both were PhD candidates with an academic background in linguistics, and both had extensive amount of EFL teaching experience in Vietnamese (Rater A for 8 years; Rater B for 8 years). As argued in Saito, Suzukida and Sun (2019), recruiting highly proficient and experienced L2 users rather than native speakers as listeners adds a degree of ecological validity to L2 speech research methodology, since such expert L2 raters are believed to be able to adequately evaluate the degree to which speakers of the same L1 are making efforts to acquire and use L2 English rather than continuously relying on their L1 systems.

The two raters first underwent a brief training session with the first author on the three different constructs of L2 phonological accuracy—(a) segmentals (substitution, omission, or insertion of individual consonant and vowel sounds) (b) word stress (misplaced or missing lexical stress in multisyllabic words); and (c) intonation (appropriate, varied use of pitch movements) (for training scripts, see **Appendix S1**). Then, each rater separately listened to the 39 speech files in a randomized

order. For each speech sample, the raters assessed the extent to which the speaker was making an effort to approximate the targetlike use of segmentals, word stress and intonation in L2 English rather than L1 Vietnamese on a 9-point scale (*1 = non-targetlike, 9 = targetlike*). The inter-rater reliability was significantly high, r = .85 for segmentals, .84 for word stress and .81 for intonation. Given that the scores of the two raters did not show any clear disagreement (defined as more than 2-point difference), the decision was made to use their averaged scores for the subsequent analyses.

Lexicogrammar Accuracy. Two different analyses of lexicogrammatical accuracy were adopted in this study: (a) subjective judgements (global weighted accuracy); and (b) corpus-based text analysis (collocation association). Foster and Wigglesworth (2016) originally proposed a four-point scale to assess the weighted accuracy of lexicogrammar in conjunction with relative impact on global understanding (*1 = very serious errors hindering meaning, 4 = entirely accurate*). Following this line of thought, Appel et al. (2019) advocated the importance of evaluating the accurate use of lexicogrammar from the perspective of comprehensibility (i.e., overall ease of understanding). Therefore, the same two expert L1 Vietnamese raters (Raters A and B) also conducted the lexicogrammar judgements. To factor out the influence of fluency-related phenomena, all filled pauses (ah, eh, oh) were eliminated from the transcripts. After the raters received training from the researcher on the definition of global lexicogrammar accuracy (for training scripts, see **Appendix S2**), they proceeded to read the 39 transcripts in a randomized order and assess each written file for global accuracy on a 9-point scale (*1 = difficult to understand, 9 = easy to understand*). Significantly high agreement was again identified, r = .87. Since no major disagreement (more than 2-point difference) was observed, their averaged scores were used as global accuracy of lexicogrammar for the subsequent analyses.

In terms of the corpus-based text analysis, a growing number of studies have shown that collocation use comprises a crucial component of L2 speech proficiency (Kyle & Crossley, 2015), and can serve as a good index of speakers' ability to use lexicogrammar appropriately in context (Saito, 2020). In general, collocation is defined as "the phenomenon surrounding the fact that certain words are more likely to occur in combination with other words in certain contexts" (Baker, Hardie, and McEnery, 2006, p. 36). One useful analytic unit of collocation is n-gram association, i.e., how often and the statistical likelihood of n words occurring together (but not with any other word). In the current study, this was operationalized using Mutual Information (MI) scores (for a comprehensive overview, see Gablasova, Brezina, & McEnery, 2017). To calculate MI scores, all the cleaned transcripts were submitted to the bigram and trigram measures available in the Tool for the Automatic Analysis of Lexical Sophistication 2.0 (TAALES) (Kyle & Crossley, 2015). MI-scores were calculated by dividing the frequency of collocations by the frequency of random co-occurrence of the words. The Corpus of Contemporary American English was chosen as the reference corpus (Davies, 2009). MI scores reflect the exclusivity of word combinations, assigning higher scores to low-frequency associations which do not have many other partner words. To create composite collocation scores for each transcript, both bigram and trigram MI scores were standardized and averaged.

Measures of Auditory Processing

As summarized in Table 1, four different aspects of participants' auditory processing abilities were measured (i.e., audio-motor integration and auditory acuity of temporal and spectral information); audio-motor integration was assessed via reproduction tasks; and auditory acuity was assessed via discrimination tasks.

Whereas L2 English speech samples were collected as a part of the EFL curriculum at the university, and as a form of individual tutoring with an instructor, it was not mandatory for participants to continue to join the auditory processing test which likely took approximately 30 minutes of their extra time. Therefore, we called for those who were willing to do the auditory test battery on a voluntary basis. To administer all the extra data collection in an efficient manner, and reduce the participants' burden, they were allowed to complete the auditory processing tests by using their computer at their convenience. To do so, the test materials were first uploaded onto our inhouse website, and piloted multiple times. Next, when interested participants contacted the researcher, she (L1 Vietnamese speaker) held a brief online meeting in which the participants received the instruction on each auditory processing test in L1 Vietnamese. All participants were explicitly instructed to engage in the test in a quiet room using their computer and headset. When the participants had any questions, they contacted the researcher to ensure that they fully understood the procedure.

In terms of the task order, the participants first engaged in the audio-motor integration task (rhythm and melody reproduction), followed by the auditory acuity task (duration, pitch, and formant discrimination). Initially, 42 participants joined our project, and completed the auditory processing tests without any problems. While we carefully monitored the participants' auditory processing performance, we found that the temporal integration performance of the three participants were not properly recorded due to some technical issues. Thus, they were eliminated from the subsequent analyses.

Audio-Motor Integration. Following the procedures used in Tierney et al. (2017), the participants completed two different audio-motor integration tasks: rhythm and melody reproduction. The rhythm reproduction task was designed to tap into one's temporal integration ability; and the melody reproduction task into one's spectral integration ability.

The rhythm reproduction task evaluated the extent to which the participants could remember easily perceptible rhythmic sequences (broader levels of temporal information) and reproduce them. In the test, the participants listened to a four-measure sequence three times, and were asked to drum out the sequence as if there were a fourth repetition. Thirty trials were presented in all, with the first 15 being "strongly metrical" and the remaining 15 being "weakly metrical" (Povel & Essens, 1985). The latter sequences contained fewer drum hits on the first and third beats than the former sequences did. The participants' drumming was quantized by changing each inter-drum-interval to the nearest interval in the set (200, 400, 600, and 800ms). The participants' response was treated as a sequence of hits and rests such that the program checked whether there was a drum hit or a rest every 200ms. The participants' sequence of hits and rests was then compared to the sequence of hits and rests in the stimulus. As a result, the ratio of correct hits and rests was calculated for rhythm integration scores. Due to technical issues, three participants' data were not properly recorded. In total, the rhythm performance of 39 participants were taken into

consideration.

As for melody reproduction, a new task was designed to evaluate the extent to which the participants could recollect and reproduce a sequence of complex tones which varied in pitch. Each melody consisted of a sequence of seven notes. Each of these notes was drawn from a set of five six-harmonic complex tones with equal amplitude across harmonics and fundamental frequencies equal to the first five notes of the major scale, corresponding to frequencies of 220, 246.9, 277.2, 311.1, and 329.6 Hz. Each note was 300 ms in duration, with a 50 ms cosine ramp at the beginning and end of the note to avoid perception of transients. No silence was interposed between notes within a melody. Melodies were pseudo-randomly constructed in the following manner. Each melody began on the third note of the scale, i.e. 277.2 Hz. The next note was then randomly chosen to be either one note higher on the scale (311.1 Hz) or one note lower on the scale(246.9 Hz). This process then repeated until all seven notes were chosen. The melody could not descend below 220 Hz or ascend above 329.6 Hz; once the melody reached these limits, the next note was chosen to either be closer to the center of the range or identical to the previous note.

During the test, participants were told that they were completing a memory test in which they were to hear melodies repeated three times, and that they were meant to try to remember them, then repeat them back. They were then played an example of a melody, repeated three times. Next, they were shown a set of five buttons vertically arranged on the screen, labeled 1 through 5. Each of these buttons, when clicked, turned from black to green in outline and played one of the five notes of the scale (with the lowest note linked to the button marked “1”, which was also arranged at the lowest point on the screen). Participants were encouraged to try clicking on these buttons to familiarize themselves with the tone linked to each button. Finally, participants were explicitly told that each melody would begin with the note linked to the button “3”. The test itself consisted of ten melodies, each of which was presented three times, with a 1-second pause in between repetitions. After these repetitions finished, the five boxes once again appeared on the screen, and participants were instructed to reproduce the melody by pressing on the boxes. As before, when they clicked each box, the tone which was linked to that number was played. Once they had completed their reproduction, they were asked to click on a “next trial” button to advance to the next melody. To assess performance, the first seven button presses produced by the participant were compared to the target melody, with identical notes scored as a 1 and notes which differed to any degree scored as a 0. Performance was then averaged across all 10 melodies.

Auditory Acuity. Three psychoacoustic tests were administered to assess the participants’ ability to capture temporal and spectral *details* of sounds: duration, pitch and formant discrimination thresholds (Surprenant & Watson, 2001). Duration discrimination thresholds were designed to assess the participants’ temporal acuity, while and pitch and formant thresholds were designed to assess their spectral acuity. For each test, 100 synthesized stimuli were created via custom MATLAB scripts. These stimuli varied along a single acoustic continuum: they either had 100 different durations, 100 different fundamental frequencies (i.e. pitch), or 100 different formant values. In each trial, three different tones were presented with an inter-stimulus interval of 0.5 s. Upon hearing each sequence, the participants were asked to choose which of the three tones differed from the other two by

pressing the number "1" or "3." Based on Levitt's (1971) adaptive threshold procedure, the size of the difference varied from trial to trial in accordance with task performance.

- **General Procedure**: Since there are 100 target samples, each file is labeled from Levels 1 to 100 (see below what each level represents in duration, pitch and formant threshold tests). The standard/anchor stimulus is labeled as Level 0. If participants can perceive the difference between the standard stimulus (Level 0) and Level 1, this represents high-level auditory sensitivity. If they can hear the difference only when they compare between the standard stimulus (Level 0) and Level 100, this indicates that their auditory sensitivity is low. To this end, the lower scores proxy the higher auditory sensitivity. Initially, the tests started from the mid-point, Level 50. In other words, in the first trial, while the two identical stimuli had a value of 0 on the target acoustic continuum (duration, pitch, or formant frequency), the different target stimulus had a value of 50. When an incorrect response was made, the difficulty of the task decreased by a degree of 10 steps (with the difference being wider). For example, if the participant answered the first trial incorrectly, for the second trial the target stimulus would have a value of 60. When they provided three consecutive correct responses, the task difficulty increased by a degree of 10 steps (with the difference being smaller). In other words, the level of the target stimulus might change from 50 to 40. The step size decreased when the direction of difficulty between trials reversed—i.e., when an increase in difficulty was followed by a decrease, or vce versa. After the first reversal, the step size changed from 10 to 5, and then after the second reversal from 5 to 1. The logic behind this feature of the test is that large changes are made to test difficulty initially to find the stimulus range where the test is difficult but not impossible, and then fine adjustments are made to test difficulty from then on so that the participant's threshold can be very precisely measured. The tests stopped either after 70 trials or eight reversals. Participants' auditory processing score was determined by averaging the stimulus levels at which the reversals occurred, starting at the third reversal. This is a measurement of the stimulus level at which the participant can just barely discriminate the stimuli. For example, one participant's third through eighth reversals were at Levels 50, 35, 40, 35, 45, and 41. This participant's score would be calculated as the average of these six numbers, or .41. This participant, therefore, can just barely tell the difference between a stimulus at level 41 and a stimulus at level 0. What each stimulus Level indicates is different across the three subtasks (Duration, Pitch & Formant Discrimination), as explained below.
- **Stimuli for Duration Discrimination**: A total of 100 four-harmonic complex tones were prepared with the fundamental frequency set to 330 Hz and equal amplitude across harmonics. The duration of the standard stimulus (Level 0) was 250 ms. To avoid the perception of transients, two amplitude ramps were included at the onset and endpoint of the stimulus (15 ms each). To differentiate the 100 tones in terms of duration (Levels 1-100), we manipulated the target acoustic dimension (duration) in steps of 2.5 ms (252.5-500 ms). For example, if a participant's reverse happens at Level "10" (out of 100), this means that the minimum difference in duration that she can hear is 25ms (i.e., 250 ms [standard

stimulus] vs. 275 ms [target stimulus]).

- **Stimuli for Pitch Discrimination**: The same 100 four-harmonic complex tones from Duration Discrimination were used. This time, however, the duration dimension remained the same throughout (i.e., 250 ms); but we set an F0 of 330 Hz as the standard stimulus (Level 0), and manipulated F0 as the target acoustic dimension for the remaining stimuli (Level 1-100). All the 100 stimuli differed between 330.3-360Hz in F0 with a step of 0.3 Hz. For example, if a participant's reversal happens at Level "10" (out of 100), this means that the minimum difference in pitch that she can hear is 3 Hz (i.e., 330 Hz [standard stimulus] vs. 333 Hz [target stimulus]).
- **Stimuli for Formant Discrimination**: A total of 100 complex tones were created. The duration of each token was 500 ms with a fundamental frequency of 100 Hz and harmonics up to 3000 Hz. Two 15 ms amplitude ramps were inserted at the beginning and endpoint of the stimulus. Using the technique of a parallel formant filter bank (Smith, 2007), three formants were generated at 500 Hz, 1500 Hz and 2500 Hz. An F2 of 1500 Hz was set for the standard stimulus (Level 0), and F2 was manipulated as the target acoustic dimension for the remaining stimuli (Level 1-100). All the 100 stimuli differed between 1502 and 1700 Hz in F2 with a step of 2 Hz. For example, if a participant's reversal happens at Level "10" (out of 100), this means that the minimum difference in formant that she can hear is 20 Hz (i.e., 1500 Hz [standard stimulus] vs. 1520 Hz [target stimulus]).
- **Calculating temporal vs. spectral acuity**: Participants' duration discrimination scores were used to index their temporal acuity. Following the method of calculating spectral acuity in the precursor research (Kachlicka et al., 2019), we standardized and averaged their pitch and formant discrimination scores. Thus, the composite spectral acuity was thought to represent their sensitivity to lower frequencies (pitch discrimination) and higher frequencies (formant discrimination).

Reliability of Reproduction and Discrimination Tasks

With respect to the reliability of audio-motor integration and acuity tasks, we conducted a follow-up study. Using the test procedure described above, a total of 30 English users with diverse experience and proficiency levels (not included in the current study) took the reproduction and discrimination tests online. To check the test-retest reliability, the same tests were delivered twice with an interval of one day. According to the results of Pearson correlation analyses (summarized in Table 5), the test instruments yielded medium-to-large test-retest effects (r = .562-.907) except for duration discrimination (r = .284). The reliability for the combined spectral discrimination scores (i.e., averaging formant and pitch discrimination scores) was r = .598, p < .001.

Importantly, the results suggest that some parts of online testing of auditory abilities (r = .907-.775 for spectral and temporal reproduction) can reach the acceptable level of reliability (Lance, Butts, & Michels, 2006), and the level of test-retest

reliability previously reported for in-lab testing (for example, $r = 0.75$ in Raz, Willerman, & Yama, 1987). However, the low reliability of the other measures ($r = .598$ and .284 for spectral and temporal discrimination) could be ascribed to several scenarios (e.g., the lack of validity, small sample size, and inconsistent sound system across participants; for more details and open data in **Brief Report**, see Saito, Sun, & Tierney, 2020).

Table 5

Results of Test-Retest Reliability for Reproduction and Discrimination Tests Used to Examine Integration and Acuity, respectively

A. Reproduction				B. Discrimination					
Spectral		Temporal		Formant		Pitch		Duration	
r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
.907	< .001	.775	< .001	.619	< .001	.562	.001	.284	.128

Results

The research question asked how auditory processing and experience factors are related to the accuracy and fluency dimensions of L2 speech learning among the 39 Vietnamese EFL learners in the classroom setting. For individual differences research of this kind, wherein there are multiple predictor and dependent variables, it is essential to examine how these variables relate to each other to avoid multicollinearity problems. Thus, the Results section first presents the auditory processing scores and their associations with experience backgrounds (the predictor variables). After we summarize the participants' L2 speech accuracy and fluency proficiency (the dependent variables), we finally present the results of multiple and mixed effects regression analyses to shed light on the complex relationship between auditory processing, experience and L2 speech proficiency.

Characteristics of Auditory Processing

According to the results of Kolmogorov-Smirnov tests, the participants' pitch discrimination scores demonstrated significant deviation from normally distributed patterns ($D = .214$, $p = .047$), whereas their formant and duration scores were comparable to normal distribution ($D = .094, .117$, $p = .846, .615$). Thus, we transformed the raw pitch scores via a log10 function. Their transformed pitch and raw formant discrimination scores were standardized and averaged to index participants' spectral acuity. The composite spectral acuity did not significantly differ from normal distribution, $D = .139$, $p = .397$. The raw duration discrimination scores were used for temporal acuity. As for audio-motor integration, both raw rhythm and melody reproduction scores did not significantly differ from normal distribution ($D = .098, .096$, $p = .810, .861$). The raw rhythm reproductionscores were used to index temporal integration; and the raw melody reproduction scores were used to index spectral integration.

For a descriptive summary of the participants' raw auditory processing scores, see **Appendix S3**. For the rest of the analyses, we used the four different dimensions of auditory processing summarized in Table 1. In the current study, spectral acuity was operationalized as combined pitch and formant discrimination scores; temporal acuity as duration discrimination scores; spectral integration as melody reproduction scores; and temporal integration as rhythm reproduction scores. In terms of the inter-relationships between integration and acuity scores, the results of Pearson correlation analyses (summarized in Table 6) found moderate correlations between temporal and spectral acuity scores (r = .438). There were no other significant associations between the integration and acuity dimensions (Bonferroni corrected: $p > .016$). As conceptualized earlier (see Table 1), this in turn suggests that integration and acuity consist of two theoretically dissociable aspects of auditory processing, at least within the current dataset.

Table 6

Inter-Relationships Between Auditory Processing Measures

	Spectral integration		Temporal acuity		Spectral acuity	
	r	*p*	*r*	*p*	*r*	*p*
Temporal integration	.307	.069	-.213	.211	-.018	.918
Spectral integration			-.002	.993	.006	.972
Temporal acuity					.438*	.005

* indicates $p < .016$ (Bonferroni corrected)

Auditory Processing and Experience

Another set of Pearson correlation analyses was performed to examine the relationship between auditory processing and language experience (see Table 7). For the rest of the analyses, the length of foreign language education is labeled as "past experience" (hours in total) and the current L2 use outside classrooms as "current experience" (hours per week). Interestingly, the results suggest that temporal integration in particular may be tied to the extent to which participants have accumulatively practiced the target language inside L2 classrooms (r = .495); and that the acuity aspect of auditory processing may be independent of experience factors.

Table 7

External Relations Between Auditory Processing and Other Influencing Factors

	Past experience	Current experience

	r	*p*	*r*	*p*
Temporal integration	.495*	.002	.331	.049
Spectral integration	.281	.084	.299	.065
Temporal acuity	-.022	.894	-.015	.929
Spectral acuity	-.096	.562	-.036	.829

* indicates $p < .025$ (Bonferroni corrected)

Characteristics of L2 Speech Proficiency

The participants' L2 fluency and accuracy performance is summarized in **Appendix S4**. The results of normality tests (Kolmogorov-Smirnov) suggested that the fluency and accuracy scores were normally distributed ($D = .073$-$.193$, $p = .093$-$.972$). To examine the inter-relationships between a total of three fluency measures and five accuracy measures, a set of Pearson correlation analyses were performed (Bonferroni corrected: $p > .007$). As summarized in Table 8, the three temporal fluency measures (articulation rate, mid-clause pause ratio, clause-final pause ratio) were significantly or marginally correlated with each other ($p < .012$). The three phonological accuracy measures (segmentals, word stress, intonation) demonstrated relatively strong associations ($r = .865$-$.875$). However, the relationship between two lexicogrammar accuracy measures (global accuracy judgements vs. collocation) remained unclear, $r = .101$, $p = .540$. Although global accuracy demonstrated marginally significant associations with clause-final pause ratio ($r = -.400$, $p = .012$), the lexicogrammar accuracy measures were not clearly clustered into the other fluent and accuracy measures. Taken together, the results suggest the following patterns at least within the current dataset. The eight outcome measures study appear to tap into four broadly different aspects of participants' L2 oral abilities—(a) temporal fluency, (b) phonological accuracy, (c) lexicogrammar accuracy, and (d) collocational use.

Table 8

Inter-Relationships Between L2 Accuracy and Fluency Measures

	Mid-clause		Clause-final		Segmentals		Word stress		Intonation		Global		Collocation	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Temporal fluency														
Articulation rate	-.624*	< .001	-.683*	< .001	-.043	.793	-.128	.437	-.058	.728	.358	.025	.217	.185
Mid-clause pause ratio			.400	.012	.017	.918	.177	.282	.103	.533	-.311	.054	.318	.048

Clause-final pause ratio	-.038	.817	.057	.730	.038	.818	-.400	.012	-.052	.755
Phonological accuracy										
Segmentals			.875*	< .001	.865*	< .001	.225	.168	-.028	.863
Word stress					.875*	< .001	.115	.486	.081	.625
Intonation										
Lexicogrammar accuracy							.212	.196	.024	.886
Global accuracy									.101	.540

* indicates $p < .007$ (Bonferroni corrected)

Roles of Auditory Processing and Experience in L2 Speech Proficiency

In order to examine the relative weights of auditory processing and experience factors in L2 speech proficiency, several regression analyses were conducted. As discussed/shown in the existing literature (Mora & Valls-Ferrer, 2012), and confirmed in the current dataset (see Table 8), a total of eight outcome measures were found to tap into four different dimensions of L2 speech proficiency

1. Phonological accuracy (segmentals, word stress & intonation)
2. Fluency (articulation rate, mid-clause pause ratio, clause-final pause ratio)
3. Lexicogrammar accuracy (global accuracy judgements)
4. Collocation accuracy (MI scores)

Therefore, we constructed a total of four different models (Models 1-4) relative to six predictors—i.e., temporal and spectral integration and acuity, past experience (total hours of foreign language education), and current experience (extracurricular L2 practice). According to the results of the power analyses (using G*Power), the observed statistical power for these models explaining a relatively large amount of variance ($f^2 = 0.35$) in the thirty-nine participants' L2 speech proficiency by way of the six predictors was .71, which could be considered acceptable in the field of applied linguistics (Larson-Hall, 2010).

For Models 1 and 2, the dependent variables are hierarchical, where same participants' performance needs to be tested three times, respectively (i.e., segmetnals, word stress, and intonation for phonological accuracy; articulation, mid-clause, and clause-final pauses for fluency). To take into random effects of subjects (being tested three times) into account, two separate

mixed effects regression models were constructed via the *lm* and *glmer* functions from the lme package (Version 1.1-21; Bates, Maechler, Bolker, & Walker, 2015) in R (R Core Team, 2018). Since the directions of articulation and pause measures were opposite (with faster speech rate and fewer pauses indicating better fluency), the latter measures were reversed.

For Models 3 and 4, the dependent variables involve one single dimension (i.e., global accuracy judgement scores for lexicogrammar accuracy; MI scores for collocation accuracy). Thus, two separate multiple regression models were constructed via the *lm* function in R. In essence, both analyses (mixed effects and multiple regression) provide the insights and values that can be interpreted in the same way, i.e., whether, to what degree and how each predictor variable is associated with dependent variables.

As summarized in Tables 9 (mixed effects modeling for Models 1 and 2) and 10 (multiple regression for Models 3 and 4), auditory processing and experience factors uniquely explained 8.1-37.9% of variance as per different dimensions of L2 speech. There was no strong evidence of multicollinearity problems (Variance Inflation Factors = 1.01-1.72). The following patterns were observed in terms of the relationship between auditory processing, experience, and L2 speech proficiency. First, the fluency measures demonstrated significant associations with amount of L2 English use outside of the classroom (extracurricular L2 practice). Second, the degree of L2 lexicogrammar accuracy (overall comprehensibility, collocational use) were primarily determined by auditory processing factors (spectral integration). Third, the driving factor of phonological accuracy was unclear. The relationship between auditory processing and L2 speech proficiency was visually summarized in Figure 1, when the experience factors were controlled for.

Table 9

Summary of Mixed-Effects Modeling Analyses

Dependent variables	Fixed effects	Standardized β	*SE*	*t*	*p*	Conditional R^2	Marginal R^2
Fluency	Temporal integration	-.137	.127	-1.081	.288	.593	.379
(articulation rate, pauses)	Spectral integration	.039	.107	0.366	.716		
	Temporal acuity	.040	.183	0.221	.826		
	Spectral acuity	-.120	.183	-0.653	.518		
	Past experience	.048	.146	0.333	.741		
	Current experience	.599	.133	4.493*	< .001		
	Random effects	Variance	*SD*				
	Participants	0.227	0.477		.		
Dependent variables	Fixed effects	Standardized β	*SE*	*t*	*p*	Conditional R^2	Marginal R^2
Phonological accuracy	Temporal integration	-.103	.197	-0.526	.603	.881	.081
(segmentals, prosody)	Spectral integration	.086	.165	0.519	.608		

Temporal acuity	-.381	.284	-1.340	.191
Spectral acuity	.124	.285	0.438	.664
Past experience	.026	.227	0.115	.909
Current experience	-.038	.206	-0.184	.855
Random effects	Variance	*SD*		
Participants	0.227	0.477		

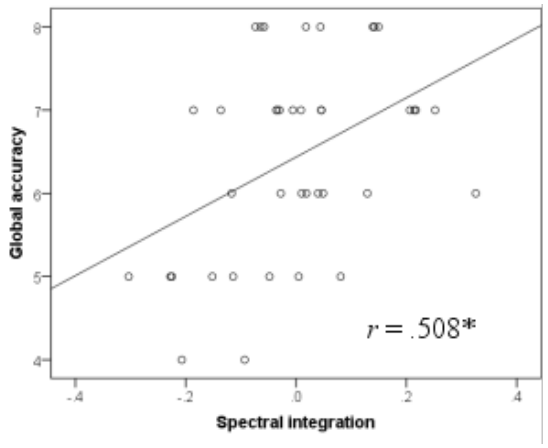
* indicates statistical significance ($p < .05$)

Table 10

Summary of Multiple Regression Analyses

Dependent variables	Fixed effects (predictors)	Standardized β	*SE*	*t*	*p*	R^2	Adjusted R^2
Lexicogrammar accuracy (global)	Temporal integration	.091	.170	0.535	.597	.469	.359
	Spectral integration	.449	.143	3.142*	.003		
	Temporal acuity	.068	.245	0.278	.782		
	Spectral acuity	-.020	.245	-0.085	.933		
	Past experience	.018	.195	0.096	.923		
	Current experience	.309	.178	1.736	.093		
Lexicogrammar accuracy (collocation)	Temporal integration	.060	.187	0.322	.7509	.298	.152
	Spectral integration	.454	.157	2.889*	.007		
	Temporal acuity	.048	.270	0.178	.859		
	Spectral acuity	-.230	.270	-0.853	.400		
	Past experience	.056	.212	-0.263	.794		
	Current experience	.075	.196	0.385	.703		

* indicates statistical significance ($p < .05$)



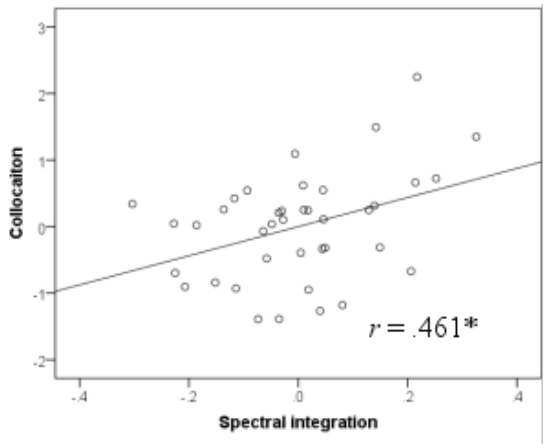


Figure 1
Correlations between Auditory Processing and L2 Speech with Experience Factors (Total Hours of Foreign Language Education, Extracurricular L2 Practice) Partialled out

Discussion

Domain-general auditory processing refers to the extent to which learners can capture and internalize broad levels of temporal and spectral information (audio-motor integration); and the extent to which they can perceive temporal and spectral details of sounds to refine the quality of auditory categorization (auditory acuity). In the L1 acquisition literature, integration and acuity measures have been shown to predict the outcomes of normal and abnormal language development (e.g., Tierney et al., 2014 for audio-motor integration; Surprenant & Watson, 2001, for spectral acuity). The main objective of the current investigation was to examine the generalizability of this construct to post-pubertal L2 speech learning in the foreign language setting. Data on auditory processing ability (audio-motor integration, auditory acuity), learning experience (quantity, quality, timing) and L2 speech profiles (fluency, phonology, lexicogrammar) were gathered from 39 Vietnamese EFL learners with an extensive amount of foreign language learning experience in classrooms (> 1000 hours) and submitted to correlation and regression analysis.

In terms of the relationship between auditory processing, experience, and L2 speech proficiency, both audio-motor integration and experience factors uniquely explained some aspects of L2 speech proficiency attainment in classroom settings. Specifically, the findings confirm our prediction that the temporal fluency aspects of L2 speech learning (articulation rate, pause ratio) are tied to learning experience, and that lexicogrammar accuracy and collocation use (global judgements, collation association) are primarily determined by auditory-motor integration. In a broad sense, these findings lead to the conclusion that (a) L2 learners can improve the fluency aspects of L2 speech, even in a foreign language setting, as long as they practice on a daily basis (Saito & Hanzawa, 2016, 2018); and (b) individual differences in the ability to perceive and reproduce auditory patterns may play a key role in the acquisition of difficult linguistic features (Li, 2016). In conjunction with Plonsky and

Ghanbar's (2018) field-specific benchmarks, the strength of the experience and audition effects could be considered as moderate-to-large (r = .40 to .60). The conclusion here generally concurs with the existing short-term training literature showing auditory processing is facilitative of the process and product of novel language learning (e.g., Wong & Perrachione, 2007). This conclusion is in line with emerging research showing that auditory processing matters for the acquisition of the relatively difficult aspect of L2 speech acquisition in naturalistic settings (i.e., accuracy rather than fluency; Saito et al., 2020, in press).

At the same time, however, we would like to emphasize that the conclusions described here need to be interpreted with some caution pending further empirical investigation and replication. Although auditory processing played a significant role according to the findings of the current study, it is important to point out that the predictive capacity of the construct may be doubtable, especially considering the asymmetric relations between the different types of auditory processing and different dimensions of L2 speech. In the current dataset, a large portion of the audition-proficiency link was actually restricted to audio-motor integration (rather than acuity) in the lexicogrammar (rather than phonological) dimensions. The asymmetric pattern here found among classroom L2 learners is different from what we previously reported among naturalistic L2 learners (e.g., Kachilicka et al., 2019 for the significant role of acuity *and* integration in phonology *and* morphology). As reviewed earlier, scholars in cognitive psychology assume the predictive power of auditory processing in acquisition, as more precise auditory processing abilities help encode and integrate aural input in a more efficient and effective fashion (Mueller et al., 2012; Tierney & Kraus, 2014). While the precursor research has shed light on the generalizability of the model to various dimensions of L2 acquisition, we now discuss the findings in the current study in order to update and fill in the theoretical details of an audition-based account of L2 acquisition. In essence, we argue that the quality and quantity of experience that learners go through (naturalistic vs. classroom) may further determine types of auditory processing abilities that learners primarily use (integration vs. acuity) and dimensions of language that auditory processing facilitates (phonology vs. lexicogrammar).

With respect to naturalistic settings, similar to L1 acquisition, L2 learners access ample aural input necessary for the simultaneous development of L2 phonology and lexicogrammar, as long as they seek opportunities to use a target language (Derwing & Munro, 2013). In such contexts, for the efficient and effective processing of every input opportunity, learners rely on both auditory integration (converting input into motor action) and acuity (conducting fine-grained analyses of input). Thus, those with more precise auditory processing can demonstrate various dimensions of advanced L2 proficiency (phonology and lexicogrammar); and the trend becomes stronger as a function of increased input (e.g., Saito et al., in press for the longitudinal relationship between auditory processing and L2 speech acquisition within the first 8 months of immersion; cf. Sun et al., in press for the first 4 months of immersion).

As for classroom L2 learning (the main focus of the current study), experience is problematic in many ways. Muñoz (2014) has pointed out that the input received by English-as-a-Foreign-Language learners is limited in source (mainly the teacher), quantity (not all teachers use the target language as the language of communication in the classroom), and quality

(there is great variability in teachers' oral fluency and general proficiency). Following our revised model of audition-based account of L2 learning, we argue that such unique characteristics of experience explain the unpredicted findings of the current study—i.e., the significant associations between lexicogrammar (rather than phonological) accuracy aspects of L2 speech learning and the integration (rather than acuity) dimension of auditory processing.

In Vietnamese EFL classrooms, adult L2 learners typically learn the target language through decontextualized teaching methods, such as grammar translation and audio-lingualism (mechanical repetition and memorization of target sentences). Although learners do receive some form of aural input from teachers (e.g., choral repetition of target sentences), the input that these approaches provide is known to be not only insufficient, but also skewed. For example, these kinds of EFL approaches are characterized by their exclusive emphasis on production (rather than comprehension) practice of lexicogrammar (rather than phonology). As shown in the current study, this could explain why auditory integration (rather than acuity) abilities could be clearly predictive of L2 lexicogrammar (rather than phonology) proficiency among our participants who went through years of EFL experience.

First, both grammar translation and audio-lingualism recommend that the target language should be mainly learned through repetitive output of oral and written sentences. While researchers have emphasized the importance of comprehension-based practice, where students receive an abundant amount of contextually-rich aural input in order to enhance understanding of language, this approach is ignored in many EFL classrooms (Shintani, Li, & Ellis, 2013). For those interested in the Vietnamese EFL setting in particular, Nguyen (2017) provides a good reference for context-specific issues related to over-reliance on grammar-translation and the significant lack of authentic L2 input. Given that students lack enough auditory, communicatively authentic input and input-based practice opportunities in order to develop, refine, and sophisticate their auditory representations, it is reasonable to assume that processing even limited input for production (audio-motor integration rather than acuity) may be a relatively key skill in successful L2 learning in EFL classrooms. This is essentially different from the acquisitionally-rich context of naturalistic L2 speech learning, where auditory integration *and* acuity are equally instrumental to success (Kachilicka et al., 2019).

Furthermore, there is a great amount of educational report revealing that the focus of instruction is exclusively on lexicogrammar, and that pronunciation training has not received enough attention in many L2 classrooms (for a review, Derwing & Munro, 2015). This may be because teachers lack adequate training experience in order to provide research-based pronunciation instruction with confidence (e.g., Burri & Baker, 2019) and/or because EFL learners prioritize the accurate use of lexicogrammar over pronunciation for the purposes of successful L2 communication (e.g., Saito, 2015). It is important to remember that previous training studies have shown a logical sequence: Auditory processing can facilitate L2 *phonological* acquisition, when learners engage in *aural* input only, and are guided to attend to *phonological* characteristics of language (e.g., Wong & Perrachione, 2007). Echoing what we found in the current study, therefore, it is unsurprising that auditory processing

could determine the degree of success in L2 lexicogrammar rather than phonology in classroom L2 speech learning, because the former is what students primarily practice and strive to improve lexicogrammar in classroosettings. Another possible explanation for why performance on the audio-motor integration test battery might relate to lexicogrammar rather than phonology is that the test battery required remembering and integrating information across a relatively long period of time (several seconds). Lexicogrammatical information is conveyed in speech across a longer time span than phonological information, and so auditory memory may be more crucial to the acquisition of lexicogrammar than phonology.

Finally, we provide tentative remarks as to the constructs of the auditory processing that we proposed and adopted in the current study. The results showed that the strength of the relationship between acuity and integration scores was not statistically significant, suggesting the two represent independent constructs (Tierney & Kraus, 2014). Given that the distinction between spectral and temporal processing reached statistical significance for acuity but not integration, we are hesitant to make any conclusive remarks on the conceptual overlap between spectral vs. temporal processing, especially in light of mixed findings from the previous literature (e.g., $r = .05$ in Kempe et al., 2015 vs. $r = .43$ in the current study). Interestingly, the participants' individual differences in integration (but not acuity) appeared to be related to L2 classroom learning experience. This finding is line with previous research showing that audio-motor integration improves as a function of language and music learning experience (Tierney, Bergeson-Dana, & Pisoni, 2008). In contrast, research has shown that auditory acuity declines as a function of chronological age (i.e., perceptual aging; Skoe et al., 2015), and that practice effects could be considered minor at best (Saito et al., in press; see Table 3). For more robust conceptual and methodological discussion on the mechanisms underlying auditory acuity and integration especially in the context of L2 acquisition, we need to wait for future studies with larger sample size.

Limitations and Future Directions

The current study took a first step towards examining the role of domain-general auditory processing in classroom L2 speech learning. Given the exploratory nature of the study, there are a number of methodological limitations that should be brought to light. In this section, we acknowledge these issues and call for future investigations to remedy them with a view of obtaining a full-fledged picture of the complex relationship between auditory processing and L2 speech acquisition.

An obvious limitation of the study was the relatively small number of learners involved ($N = 39$). In the current investigation, we found significant effects for auditory processing and experience on L2 lexicogrammar accuracy and fluency but not for phonological accuracy. However, the small sample used put the results at greater risk for Type I or Type II error. The *true* presence and absence of the relationship between auditory processing, experience, and L2 speech proficiency needs to be tested with sufficiently large sample size. The generalizability of the results should also be treated with caution. We stress that the findings presented here should be interpreted solely according to the particular group of L2 learners involved (college-level Vietnamese learners of English). We recommend that future replication studies use more participants with a wider range of proficiency levels (e.g., low, mid, high, and near-nativelike L2 proficiency; Abrahamsson & Hyltenstam, 2009), classroom

experience (e.g., language vs. content-based classes; Saito & Hanzawa, 2018), and L1-L2 parings (e.g., linguistically close vs. distant; McAllister, Flege, & Piske, 2002). To further broaden our understanding of this relationship, future research should also feature different speaking tasks (formal vs. informal; Crowther, Trofimovich, Isaacs, & Saito, 2015), speech analysis techniques (e.g., acoustic vs. rater judgments; Saito & Plonsky, 2019), and auditory processing instruments (e.g., explicit vs. implicit; Saito, Sun, & Tierney, 2019).

Relatedly, due to the small sample size, it is important to stress that any conclusions regarding the constructs of the auditory processing that we proposed and adopted in the current study could be tentative. The results showed that the strength of the relationship between acuity and integration scores was not statistically significant, suggesting the two represent independent constructs (Tierney & Kraus, 2014). Given that the distinction between spectral and temporal processing reached statistical significance for acuity but not integration, we are hesitant to make any conclusive remarks on the conceptual overlap between spectral vs. temporal processing, especially in light of mixed findings from the previous literature (e.g., $r = .05$ in Kempe et al., 2015 vs. $r = .43$ in the current study). Interestingly, the participants' individual differences in integration (but not acuity) appeared to be related to L2 classroom learning experience. This finding is line with previous research showing that audio-motor integration improves as a function of language and music learning experience (Tierney, Bergeson-Dana, & Pisoni, 2008). In contrast, research has shown that auditory acuity declines as a function of chronological age (i.e., perceptual aging; Skoe et al., 2015), and that practice effects could be considered minor at best (Saito et al., in press). For more methodological recommendations, see Brief Report in Saito et al. (2020).

The third limitation is the possibility, which we cannot at present rule out, that the auditory processing tasks (reproduction, discrimination) used in the study may have conflated a range of modality-general executive function skills (e.g., attentional control, processing speed, memory). While we have demonstrated links between auditory perception and L2 speech learning, it is still unclear the extent to which individual differences in auditory processing are distinguishable from variability in higher-order cognitive abilities upon which auditory perception may draw. This issue aligns with concerns also present in the L1 acquisition literature about the construct validity of auditory processing tests (e.g., Snowling, Gooch, McArthur, & Hulme, 2018). For example, the audio-motor integration task requires participants to selectively attend to and store melodic and rhythmic sequences for a short period of time in the brain, and then reproduce them with good motor control. There is some research evidence that L2 speech acquisition may be mediated by various components of cognitive abilities (Darcy, Mora, & Daidone, 2016 for inhibitory control; O'Brien, Segalowitz, Collentine, & Freed, 2006 for phonological short-term memory; Reiterer et al., 2011 for working memory). It would be interesting to further examine whether the relationship between audio-motor integration and classroom L2 speech learning remains significant even after participants' phonological short-term memory and processing speed are factored out. Future studies should adopt both auditory processing and cognitive measures within the same research design so as to check the degree of independence between auditory processing and cognitive abilities and

investigate the *separate* effects of auditory processing and cognitive abilities on the process and product of learning.

Finally, we need to acknowledge that all the auditory processing data were collected online rather than via face-to-face meetings. Although we made efforts to ensure that the participants followed the procedure and completed the test in a quiet room, three out of 42 participants, who originally joined the current study, had to be eliminated due to their confusion and technical difficulties (i.e., less than 10% of attrition). Due to the current climate, researchers are urgently encouraged to avoid face-to-face meetings, and collect data online. We strongly believe that more future studies are needed to not only examine the reliability and validity of the *online* auditory processing tests, but also suggest and introduce improvements to such online data collection platforms. As reported earlier, the test-retest reliability of the online auditory processing tests (reproduction, discrimination) was somewhat varied (r = .284-.907). The results here are different from what previous cognitive psychology literature typically reported about the reliability of the auditory processing measures in laboratory settings (r = 0.75 in Raz et al., 1987). This indicates that while the task format of the auditory processing tests has been well accepted (see also Moore, 2012 for an overview of auditory processing test formats in L1 and hearing research), the possibility of delivering the test online remains open to further discussion, validation, and refinement.

It is crucial to stress again that the results of the reliability analyses derived from our small-scale pilot research (Saito et al., 2020 for n = 30 L1 and L2 English speakers). In order to find the *true* presence or absence of satisfactory test-retest reliability, we plan to expand the dataset with larger sample size in order to redo the analyses with sufficiently strong statistical power. As a reviewer pointed out, another reason for the inherent difficulties of online testing is technological in nature. That is, fine control cannot be maintained over stimulus loudness across participants, given that they are using their own computers with different hardware and sound settings, which could contribute to this range of test reliability. More work is needed on how to help deliver the identical test settings for participants regardless of their contexts (see Nagle, 2020 for his interesting reliability and validation study on the implementation of online L2 speech ratings and analyses via Amazon Mechanical Turk).

Conclusion

Research to date has shown that auditory acuity and integration are primary determinants of L1 acquisition (e.g., Tierney et al., 2014) and of L2 phonological and lexicogrammar acquisition in *naturalistic* settings (e.g., Kachlicka et al., 2019; Saito et al., 2020). The current study extended this line of work to a classroom foreign language setting, showing that auditory processing effects are limited to specific dimensions of auditory processing (integration) and speech learning (lexicogrammar). These findings may reflect how the participants in the current study (Vietnamese EFL students) usually practice the target language (e.g., through production-based grammar translation practice), and the lack of authentic input exposure that is typical of this setting (which impedes thdevelopment/refinement of auditory acuity). All in all, the study agrees with the audition-based account of language learning that domain-general auditory processing could be an important source of individual differences in language learning throughout the life (Goswami, 2015; Mueller et al., 2012; Tierney & Kraus, 2017). However, we add that the

type of learning experience (i.e., naturalistic vs. classroom) could influence which auditory processing abilities learners draw on (integration and/or acuity), and which dimensions of language rely on auditory processing (phonology vs. lexicogrammar).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1. Training Materials for Phonological Accuracy.

Appendix S2. Training Materials for Lexical Accuracy.

Appendix S3. Descriptive Statistics of Raw Auditory Processing Scores.

Appendix S4. Descriptive Statistics of Raw Speech Scores.