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Revisiting the association between musical expertise and second-language proficiency

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Musical expertise is frequently correlated with second-language (L2) proficiency, but it remains unclear whether this association generalizes across languages and measures. Here, we examined links between musical expertise and L2 proficiency among native speakers of Portuguese (Study 1) and Polish (Study 2). L2 (English) proficiency was assessed with both self-reports and objective tests of pragmatic competence. Musical expertise was defined as music training and musical ability, with ability assessed via self-reports and objective tests of melody and rhythm perception. In Study 1 (Portugal, n = 146), musical expertise showed no associations with L2 proficiency. In Study 2 (Poland, n = 174), after accounting for demographic variables and non-verbal reasoning, L2 proficiency correlated positively with self-reported musical ability, but not with music training or melody or rhythm perception. These findings suggest that links between musical expertise and L2 proficiency are weak, inconsistent, or contingent on how L2 proficiency is defined and measured.

1. Introduction

Is musical expertise predictive of language proficiency? Whereas an association would suggest shared neurocognitive mechanisms, no association would indicate independent processing. Identifying the magnitude of any association could also help to clarify the limits of plasticity and transfer, with potential practical implications, such as informing interventions that use training in one domain (e.g. rhythm) to ameliorate deficits in another domain (e.g. dyslexia; [1,2]). Because virtually all typically developing adults are fluent in their native language (L1), here we asked whether musical expertise predicts proficiency in a second language (L2), which shows greater individual variation.

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Several theoretical perspectives predict links between music and language. One view emphasizes the role of rhythm abilities [3], based on findings indicating that impaired temporal perception predicts speech and language disorders [4–6]. For example, at two months of age, infants at risk for dyslexia exhibit reduced mismatch-negativity responses to temporal changes [7]. Even among typically developing children, temporal perception is associated modestly with reading, speech and other L1 abilities [8–11].

Other perspectives are more vague about the underlying mechanisms that are involved. One, the MAPLE (Musical Abilities, Pleiotropy, Language and Environment) framework [12], proposes that associations with typical language development extend beyond rhythm to *musicality* in general (i.e. naturally developing musical traits; [13]), based on common genetic influences and overlapping neural substrates. Another, the OPERA (Overlap, Precision, Emotion, Repetition and Attention) hypothesis [14–16], posits that music training improves speech perception (e.g. speech in noise [17]), because compared with speech, music requires more precise sound encoding, which training reinforces through extensive repetition, focused attention and emotional engagement. These enhancements are proposed to extend further to higher-order language abilities such as reading [14,18,19]. Meta-analyses of longitudinal studies confirm that music training has a small positive association with L1 phonological awareness in childhood [20] and with auditory and linguistic processing across age groups [21].

For proficiency in L2, a meta-analysis of 57 studies reported a positive association with musical expertise [22]. The magnitude of the link did not differ whether musical expertise was defined as music training (e.g. trained vs untrained; years of lessons) or as musical ability, which is typically measured with objective tests of music-perception ability. Because the analyses did not distinguish training from ability, it remains unclear whether both factors contributed independently. In one study of Finnish adults, musical ability correlated with L2 (English) phoneme pronunciation and discrimination even after accounting for training [23]. In another study, when English-speaking children and adults were required to discriminate L2 (Zulu) speech sounds, musical ability predicted performance better than music training did [11,24]. It is therefore important to include tests of musical ability, because, if music training does not add additional power when predicting non-musical associations, such associations could stem from predispositions, specifically individual differences in musical aptitude or listening abilities. This possibility becomes even more likely if musical ability predicts language ability even after accounting for the effects of music training.

Associations between L2 ability and musical expertise could also depend on the specific measures or languages involved. If rhythm plays a central role, associations should emerge primarily for tasks measuring temporal processing. Languages can also be tonal (e.g. Mandarin) or non-tonal (e.g. German), and syllable-timed (e.g. French) or stress-timed (e.g. English). For native speakers of French, Bhatara *et al.* [25] reported that years of L2 study (primarily English) were predicted by rhythm perception but not by melody perception. Nevertheless, a similar study of speakers of European Portuguese (stress-timed) found no association between self-reported L2 (English) skills and musical expertise measured as training, melody perception or rhythm perception [26]. Moreover, Bayesian analysis provided substantial evidence for the null hypotheses, indicating that L2 ability was independent of both music training and rhythm perception. These null results present a challenge for claims of links between language ability and musical expertise, whether broad [12] or rhythm-specific [6,27]. Alternatively, such links could depend on whether the languages involved are syllable- or stress-timed.

A related issue concerns how L2 proficiency is defined and measured. Proposals of associations between musical expertise and language suggest that such associations extend beyond auditory processing (e.g. phonology) to reading [19] or to language-related abilities defined broadly [12,22]. In Thompson *et al.*'s [22] meta-analysis, most of the studies (56.5%) assessed the perception or production of phonemes from a *novel* L2 rather than proficiency in a learned language. In other words, these tasks relied exclusively on listening skills. As one might expect, associations with musical expertise were stronger for these novel-language studies than for studies of actual proficiency. Nevertheless, in addition to being able to discriminate the component phonemes, L2 proficiency requires an extensive vocabulary, morphological and syntactical knowledge, as well as familiarity with idioms and how a specific L2 is used in context. Moreover, even if the link with musical expertise and L2 phonology is reliable, it remains uninformative in terms of causation. Domain-general auditory abilities could predict the perception and production of unfamiliar speech sounds, just as they predict music training and musical ability [28].

L2 proficiency is also measured frequently with self-reports, which could be only indirectly associated with actual proficiency. For example, individuals who report studying one or more L2s for several years [25] may not be proficient in any of them. Self-reports of actual ability can also correlate with extraneous factors such as general cognitive ability [26], and they could be inaccurate, inflating or attenuating associations with musical measures.

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Here, we examined L2 (English) skills among native speakers of European Portuguese (Study 1) and Polish (Study 2). L2 was the same across studies (English, stress-timed), but L1 was stress- or syllable-timed. L2 proficiency was assessed with both self-reports and objective tests, which allowed us to examine how well self-reports reflect actual ability and whether associations with musical expertise depend on measurement approaches. Our objective tests of L2 proficiency assessed *pragmatic competence* (i.e. appropriate use of language in context), allowing us to ask directly whether associations with musical expertise extend beyond low-level listening skills. We also accounted for potential confounding factors, including non-verbal reasoning, age, gender and education. Although Thompson *et al.* [22] reported a small but significant association between musical expertise and L2 capabilities defined broadly, the null findings from Schellenberg *et al.* [26] led us to question whether such associations would generalize to measures of pragmatic competence. The research protocol for Studies 1 and 2 was approved by the local ethics committee at Iscte – University Institute of Lisbon.

2. Study 1—Portugal

2.1. Method

2.1.1. Participants

The sample comprised 146 native speakers of Portuguese (112 women, 33 men, 1 unspecified) recruited from a university community in Lisbon. Participants ranged in age from 18 to 60 years (mean = 23.90, s.d. = 9.15). Because the age distribution was skewed positively and only 16 participants were over 30, age was square-root transformed for statistical analyses. Gender was dummy coded (male = 1).

Six participants had not finished high school, 83 were primarily undergraduates who had a high-school diploma, 43 had a bachelor's degree, and 14 had a master's degree or PhD. Education was treated as a four-level ordinal variable. Responses to item 36 from the Goldsmiths Musical Sophistication Index (Gold-MSI; [29]) confirmed that participants varied widely in music training, with 81 (55.48%) reporting no formal training, 4 (2.74%) half a year, 4 (2.74%) 1 year, 14 (9.59%) 2 years, 24 (16.44%) 3–5 years, 11 (7.53%) 6–9 years and 8 (5.48%) at least 10 years.

Post hoc power analysis considered the mean effect size of $z = 0.32$ (Fisher's r to z transformation, excluding five outliers with unusually large effect sizes) from Thompson *et al.* [22], which we transformed back to $r = 0.31$. G*Power [30] indicated that our sample of 146 participants provided abundant power (97.5%) to detect a correlation of this magnitude or larger (two-tailed test).

2.1.2. Materials

L2. L2 Proficiency was measured using self-reports and an objective test of English comprehension. The self-report measure, from Swaminathan *et al.* [31], was translated into Portuguese by Schellenberg *et al.* [26]. It comprised seven items that assessed multifaceted proficiency in English. Specifically, participants used 7-point scales (1 = no knowledge, 7 = perfect knowledge) to rate their skills in speaking, reading, writing, comprehension, fluency, vocabulary and accent.

The objective measure of L2 proficiency (hereafter L2 comprehension) was the General English Test (GET), a 25-item, multiple-choice online measure developed by Cambridge University Press (https://www.cambridgeenglish.org/test-your-english/general-english/). The first five items had three response options. One example was: *Can I park here?* Response options were: *Sorry, I did that*; *It's the same place*; and *Only for half an hour*. The remaining 20 items had four options. One example was: *She came to live here* _____ *a month ago*, with response options *quite*, *beyond*, *already* and *almost*. Scores were the number of correct responses.

Detailed descriptions of other tasks and measures used in the present report can be found in Correia *et al.* [32].

Musical expertise. We defined musical expertise in five ways. Three were derived from a self-report questionnaire and two from objective testing. Self-reports were collected with the Gold-MSI ([29]; Portuguese version, [33]), which had 38 items that form five subscales. One, the music training subscale, served as our principal measure of *music training*.[1] In addition to years of music lessons, it included items about practice duration and frequency, music theory, compliments on performance and self-identification as a musician. To be consistent with the literature [34], we also considered a single item from this

[1]We use title case to distinguish measured variables from constructs.

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subscale (item 36, hereafter years of lessons), which measured years of lessons on a 7-point ordinal scale (see §2.1.1 for frequency distribution). In a sample of over 1200 participants, scores on this item correlated almost perfectly with exact years of music training, square-root transformed to reduce positive skew ($r = 0.953$; [35]). A separate measure (hereafter, musicality self-reports) was formed by standardizing and averaging scores on two other subscales: perceptual ability (e.g. *I have trouble recognizing a familiar song when played in a different way or by a different performer*, reverse coded) and singing ability (e.g. *After hearing a new song two or three times, I can usually sing it by myself*).

The two objective measures came from the Musical Ear Test (MET; [36]), which assessed listeners' ability to perceive, remember and discriminate short auditory sequences. On each of 104 trials, listeners judged whether two sequences were identical. The first half (melody subtest; 52 trials) comprised standard and comparison sequences of piano tones that were isochronous but varied in pitch; on non-identical trials, at least one tone of the comparison sequence was shifted upward or downward. The second half (rhythm subtest; 52 trials) was identical, except sequences comprised wood-block tones that varied in inter-onset intervals but not in pitch; on non-identical trials, at least one inter-onset interval was changed. For both subtests, scores were the number of correct responses. Scores from participants with 10 or more consecutive missing or incorrect responses were excluded for failing to attend to the task. The online version of the MET [32] used here retains the good psychometric properties of the original test [31].

Control measures. In addition to demographic variables, we measured non-verbal reasoning with the Matrix Reasoning Item Bank (MaRs-IB; [37]; available at https://app.gorilla.sc/openmaterials/36164), an 8 min online measure modelled after Raven's Advanced Progressive Matrices (for details, see [32,38,39]). Scores were the proportion of correct responses, logit-transformed as in previous research [26,28,32,38–40]. Personality was measured with the online version [32] of the Portuguese translation [41] of the Big Five Inventory [42]. The scale included 44 items and took approximately 5 min to complete. Items were averaged to form separate scores for openness-to-experience (hereafter *openness*), conscientiousness, extroversion, agreeableness and neuroticism.

2.1.3. Procedure

Participants completed a single online session lasting 45–60 min. All questionnaires and tasks were implemented using Gorilla Experiment Builder ([43]; www.gorilla.sc). Before testing began, an experimenter ensured via Zoom that participants were in a quiet environment, wearing headphones and had sound notifications muted on their devices. After providing informed consent, the participants completed the questionnaires and objective-ability tests in a fixed order: L2 self-reports, Gold-MSI, GET, MaRs-IB, Big Five Inventory (BFI) and MET. At the end of the session, participants received feedback about their musical abilities, personality traits and GET scores. Testing was conducted in the winter and autumn semesters of 2023.

2.1.4. Data analysis

Analyses included both Bayesian and standard frequentist statistics (i.e. null hypothesis statistical testing, NHST) conducted with JASP 0.19.3 ([44]; default priors). Unlike NHST, which evaluates the likelihood of the observed data if the null hypothesis is true, Bayes factors (BF_{10}) compare the likelihood of the data under the alternative or null hypothesis. A BF_{10} (reported here with three-digit accuracy) of 1.00 indicated that the data were equally likely under both hypotheses, whereas values greater or less than 1.00 indicated support for the alternative or null hypothesis, respectively. Following Jeffreys [45], ratios of 3 or greater were considered to provide at least substantial evidence for the alternative ($BF_{10} > 3.00$) or null hypothesis ($BF_{10} < 0.333$). Otherwise, evidence was considered weak. Values of 10.0, 30.0 or 100 (or less than or equal to 0.100, 0.033 or 0.001) corresponded to strong, very strong or decisive evidence, respectively. We considered results to be reliable only if Bayesian evidence was substantial or stronger.

2.2. Results and discussion

Mean ratings for the seven items from the L2 self-report questionnaire (supplementary material, table S1) varied significantly in magnitude, $F(6, 870) = 63.49$, $p < 0.001$, partial $\eta^2 = 0.305$, $BF_{10} > 100$, ranging from

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Table 1. Descriptive statistics for measures of L2 proficiency and musical expertise in Study 1 (Portugal).

variable	*n*	*M*	s.d.	range
L2 proficiency				
L2 self-reports	146	0.00	1.00	−3.26 to 1.52
L2-comprehension	146	19.34	4.01	4–25
musical expertise				
music training	146	2.81	1.50	1.00–6.29
years of lessons	146	2.73	2.12	1–7
musicality self-reports	146	0.00	0.91	−2.34 to 2.05
melody	131	34.27	5.83	20–51
rhythm	138	35.70	5.90	21–46

Note: years of lessons were measured on a 7-point ordinal scale, with 1 = 0 years, 2 = 0.5 years, 3 = 1 year, 4 = 2 years, 5 = 3–5 years, 6 = 6–9 years, and 7 = 10 or more years.

4.47 (accent) to 5.79 (comprehension). Because items were highly intercorrelated $0.558 \le r \le 0.898$, *p*s < 0.001, $\mathrm{BFs}_{10} > 100$, we extracted the principal component (hereafter L2 self-reports), which accounted for 78.5% of the variance in the original items. Loadings ranged from 0.824 to 0.947.

Table 1 provides descriptive statistics for the L2 and musical-expertise measures. Preliminary analyses examined pairwise associations between the two L2 measures and the nine control variables (i.e. age, gender, education, non-verbal reasoning and five personality traits; supplementary material, table S2). Bayesian analyses provided strong evidence that non-verbal reasoning predicted L2 comprehension, $r = 0.275$, $p < 0.001$, $\mathrm{BF}_{10} = 28.0$, but not L2 self-reports, $r = 0.211$, $p = 0.011$, $\mathrm{BF}_{10} = 2.63$. Age had negative correlations with L2 self-reports, $r = -0.201$, $p = 0.015$, $\mathrm{BF}_{10} = 1.95$, and L2 comprehension, $r = -0.170$, $p = 0.040$, $\mathrm{BF}_{10} = 0.831$, which Bayesian analyses deemed weak. For 12 of the remaining 15 tests, the data provided substantial evidence for no association. For the other three, evidence was weak for both hypotheses. Based on these findings, all subsequent analyses used partial correlations controlling for non-verbal reasoning and age. Gender and education were included as additional covariates to maintain comparability with Schellenberg *et al.* [26].

The correlation between L2 self-reports and L2 comprehension was high, $r = 0.686$, $p < 0.001$, $\mathrm{BF}_{10} > 100$, indicating that 47% of the variance (independent of four covariates) was shared. This association provided support for the construct validity of both measures and for the results from previous tests of associations between musical expertise and our self-report measure of L2 proficiency [26,31].

Pairwise partial associations among the five musical-expertise measures (music training, years of lessons, musicality self-reports, melody and rhythm) are provided in supplementary material, table S3. There was decisive evidence that the two objective tests of musical ability (rhythm and melody) were correlated, and decisive or very strong evidence for positive associations between all pairwise combinations of music training, years of lessons, musicality self-reports and melody. The evidence was weaker but still substantial for an association between rhythm and music training, but not for associations between rhythm and musicality self-reports or years of lessons.

The principal analyses examined partial associations between musical expertise and L2 proficiency (table 2). The data provided substantial evidence that music training, years of lessons and musicality self-reports were *not* associated with either L2 self-reports or L2 comprehension. Melody and rhythm also showed no associations with either measure of L2 proficiency, although evidence for the null hypotheses was weak. The results did not change when we examined simple instead of partial correlations (supplementary material, table S4). Thus, adjusting for covariates had theoretical but no practical importance.

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Table 2. Partial correlations (Pearson *r*, *p* values and Bayes factors) in Study 1 (Portugal) between musical expertise and L2 proficiency. Non-verbal reasoning, gender, age and education were held constant.

	L2 self-reports			L2 comprehension		
musical expertise	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}
music training	−0.008	0.925	0.104	−0.045	0.594	0.120
years of lessons	0.089	0.293	0.182	0.069	0.415	0.145
musicality self-reports	0.079	0.350	0.162	−0.090	0.285	0.185
melody	0.150	0.093	0.448	0.154	0.083	0.490
rhythm	0.184	0.033	1.04	0.166	0.055	0.688

In sum, the correlation between L2 self-reports and L2 comprehension provided support for the validity of both measures. The absence of associations with musical expertise belied the conclusions of Thompson *et al.* [22] but was consistent with previous results from a similar sample of Portuguese speakers [26]. The findings suggest that associations between musical expertise and L2 proficiency are weak or contingent on specific populations, definitions or measures. We tested this possibility further in Study 2, which asked Polish speakers to complete the same self-report measure of L2 proficiency used in Study 1, but a different objective test of pragmatic competence, which provided separate scores for reading and listening.

3. Study 2—Poland

3.1. Method

3.1.1. Participants

We recruited 174 adults from a university community in Warsaw who were native speakers of Polish (62 men, 110 women, 2 unspecified). Gender was dummy coded as in Study 1. Age ranged from 18 to 66 years (mean = 23.90, s.d. = 9.15) and was again square-root transformed. Except for four participants, most (n = 142) were undergraduates who had finished high school. Others had a bachelor's degree (n = 10) or a postgraduate degree (n = 18). Education was again treated as a four-level ordinal variable. Item 36 from the Gold-MSI indicated that 116 participants (66.7%) had no history of music training, six had half a year (3.45%), nine (5.17%) had 1 year, four (2.30%) had 2 years, 22 (12.64%) had 3–5 years, 11 (6.32%) had 6–9 years, and six (3.45%) had at least 10 years. Post hoc power analysis confirmed that our sample size provided ample power (99.0%) to detect an association that matched or exceeded the average reported by Thompson *et al.* [22].

3.1.2. Measures

L2 proficiency was measured with the same self-report questionnaire used in Study 1 but with a different objective test of English proficiency. Instead of the GET, we used the reading and listening subtests from the EF Standard English (Practice) Test (EF SET, www.efset.org), hereafter called L2-reading and L2-listening. Like the GET, both subtests measured pragmatic competence. Both were available in two equivalent versions, with participants assigned randomly to one version. Each had a 7.5 min time limit and 10 multiple-choice items, with four response options per item. One L2-reading item was *In order to find him, they needed to know his exact* ________, with response options: *location*, *place*, *site* and *setting*. In the L2-listening subtest, participants heard a spoken phrase and selected the correct response from four written alternatives. One example was: *I'm taking four lecture courses and attending eight seminars this semester*, spoken by a man with a mid-Atlantic accent. Response options were: *So you barely study at all, You're really hardworking, You're hardly working* and *You have lots of leisure time.* Participants could choose to hear the phrase a second time before responding. Scores were the number of correct responses.

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Table 3. Descriptive statistics for measures of L2 proficiency and musical expertise in Study 2 (Poland).

variable	*n*	*M*	s.d.	range
L2 proficiency				
L2 self-reports	174	0.00	1.00	−3.19 to 1.90
L2-reading	174	7.60	1.73	1–10
L2 listening	174	7.70	2.61	0–10
musical expertise				
music training	174	2.51	1.35	1.00–7.00
years of lessons	174	2.24	1.95	1–7
musicality self-reports	174	0.00	0.89	−2.64 to 2.05
melody	141	32.11	5.87	19–48
rhythm	154	33.81	5.76	19–44

Note: years of lessons were measured on a 7-point ordinal scale, with 1 = 0 years, 2 = 0.5 years, 3 = 1 year, 4 = 2 years, 5 = 3–5 years, 6 = 6–9 years, and 7 = 10 or more years.

The control variables and five measures of musical expertise were identical to those in Study 1, but the Gold-MSI and the BFI were administered in Polish instead of Portuguese.

3.1.3. Procedure

The procedure was identical to Study 1 except that the test of L2 proficiency differed. The two L2 subtests were presented in a fixed order: L2-reading followed by L2-listening. Testing occurred during February and April of 2023.

3.2. Results and discussion

We asked first whether self-reported L2 proficiency differed from that of Study 1. Strong evidence indicated that Polish participants (mean = 4.73, s.d. = 1.19) provided lower ratings (averaged across the seven items) compared with Portuguese participants (mean = 5.15, s.d. = 1.21), $t(318) = 3.09$, $p = 0.002$, Cohen's $d = 0.346$, $BF_{10} = 11.3$. As in Study 1 (supplementary material, table S1), means varied reliably, from 4.25 (accent) to 5.53 (reading), $F(6, 1038) = 40.94$, $p < 0.001$, partial $\eta^2 = 0.191$, $BF_{10} > 100$, but the seven items were highly intercorrelated, $0.401 \le r \le 0.832$, ps < 0.001, $BFs_{10} > 100$. A principal component (L2 self-reports) accounted for 70.7% of the variance, with loadings ranging from 0.749 to 0.906.

Descriptive statistics for the L2 and musical-expertise measures are provided in table 3. Tests of pairwise associations between the three measures of L2 proficiency and the nine control variables (supplementary material, table S5) revealed that non-verbal reasoning predicted both L2 self-reports, $r = 0.234$, $p = 0.002$, $BF_{10} = 11.2$, and L2-listening, $r = 0.210$, $p = 0.006$, $BF_{10} = 4.31$. For the other 25 tests, the data favoured the null hypothesis, with all $BF_{10} < 1.00$, with substantial evidence in 21 tests. As in Study 1, non-verbal reasoning, age, gender and education were held constant in all subsequent analyses.

Strong partial pairwise correlations among the three L2 measures provided evidence for their construct validity. After adjusting for the four covariates, the data provided decisive evidence that L2-reading and L2-listening were correlated positively, $r = 0.468$, and that L2 self-reports predicted both L2-reading, $r = 0.465$, and L2-listening, $r = 0.510$, ps < 0.001, $BFs_{10} > 100$.

Pairwise partial associations among the musical-expertise variables (adjusted for covariates) are provided in supplementary material, table S6. As in Study 1, there was decisive evidence for an association between melody and rhythm, and for each pairwise combination of four of five measures (music training, years of lessons, musicality self-reports and melody). Rhythm was again an exception, with substantial

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Table 4. Partial correlations (Pearson *r*, *p* values and Bayes factors) in Study 2 (Poland) between musical expertise and L2 proficiency. Non-verbal reasoning, age, gender and education were held constant.

	L2 self-reports			L2 reading			L2 listening		
musical expertise	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}	*r*	*p*	BF_{10}
music training	0.106	0.168	0.249	0.126	0.101	0.373	0.069	0.374	0.142
years of lessons	0.089	0.246	0.188	0.126	0.100	0.373	0.086	0.267	0.177
musicality self-reports	0.253	< 0.001	26.5	0.217	0.005	5.62	0.139	0.070	0.501
melody	0.105	0.222	0.223	0.078	0.364	0.160	0.139	0.105	0.400
rhythm	0.175	0.032	1.01	0.030	0.713	0.108	0.190	0.020	1.58

evidence for no correlation with either music training or years of lessons, and weak evidence for an association with musicality self-reports.

The main analyses examined pairwise partial associations between the three measures of L2 proficiency and the five measures of musical expertise (table 4). In 7 of 15 instances, there was substantial evidence for the *null* hypothesis—no association between L2 proficiency and musical expertise. Specifically, L2 self-reports had no association with music training, years of lessons, or musicality self-reports; L2-reading had no association with melody or rhythm; and L2-listening had no association with music training or years of lessons. In six instances, evidence for an association was weak, but similarly weak for the null hypothesis. In the remaining two instances, there was strong and substantial evidence that musicality self-reports correlated positively with L2 self-reports and L2-reading, respectively. Simple associations between L2 and musical expertise (supplementary material, table S7) were identical except in one instance: there was substantial evidence for a simple association between L2-listening and rhythm, which was not evident after adjusting for the covariates. Thus, in Study 2, controlling for extraneous individual differences had both theoretical and practical importance. In any event, the significant simple association between L2-listening and rhythm ($p = 0.008$) would fail to withstand correction for multiple (15) tests.

In short, correlations among the three measures of L2 proficiency provided evidence for their construct validity. As in Study 1, the results were largely inconsistent with the conclusions of Thompson *et al.* [22], except for observed associations between musicality self-reports and L2 proficiency.

4. General discussion

In two studies with relatively large samples ($n > 140$), we asked whether L2 (English) proficiency was associated with musical expertise. Participants came from populations with two different L1s (Portuguese or Polish), L2 proficiency was measured with self-reports and objective tests of pragmatic competence, and musical expertise was defined as music training, self-reported musical abilities and performance on objective tests of melody and rhythm perception. In Study 1, there was no evidence that musical expertise predicted L2 proficiency. Bayesian analyses provided substantial support for null associations between L2 proficiency and both music training and self-reported musical abilities.

Results from Study 2 were similar to those from Study 1, suggesting that associations between L2 proficiency and musical expertise do not depend on whether L1 and/or L2 are stress- or syllable-timed. As in Study 1, L2 proficiency was unrelated to music training or performance on objective tests of musical ability. Moreover, in 7 of 15 tests, the observed data provided substantial support for the null hypothesis. In the two instances when substantial or greater evidence emerged for a positive association after adjusting for the covariates, musical ability was measured with self-reports. Polish participants who provided higher ratings of their music perception and singing abilities also tended to report higher levels of L2 proficiency and to perform better on a reading comprehension test. These associations may reflect, at least in part, increased attentiveness to task demands or socially desirable responding. In any case, theories proposing links between music and language focus specifically on music training (e.g. [14–16]) or natural musical ability (e.g. [12]), and not on self-reports of perceptual or singing abilities.

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How can we reconcile our weak findings with Thompson *et al.*'s [22] conclusion that musical expertise is associated positively with L2 ability? One possibility is that such links are more likely to emerge for tests of speech perception than for measures of pragmatic competence or self-reports. In line with this view, Slevc and Miyake [46] reported that musical ability was correlated with the production and perception of L2 phonology, but not with L2 vocabulary or syntax. Indeed, 80% of the effect sizes in Thompson *et al.* [22] involved L2 phonology. Although their test of moderation that compared phonological and non-phonological outcomes was not significant, three phonology studies were excluded because of unusually large effect sizes. Another possibility is that associations with musical expertise are more likely in early stages of L2 learning, when learners acquire basic lexical or phonological distinctions (e.g. days of the week and how to count), than in later stages that require comprehension of idiomatic or pragmatic meaning. In the present investigation, associations were particularly weak among Portuguese participants, who reported higher L2 proficiency than their Polish counterparts.

Moreover, studies rarely account for confounding variables when examining associations with musical expertise (for a review, see [47]), and Thompson *et al.*'s [22] conclusion was based on simple associations even though findings can change when covariates are included. The conservative approach taken in the present report is commensurate with recent large-scale, pre-registered, replication-oriented, multi-laboratory studies that examined non-musical associations with musical expertise. One asked whether musicians have superior short-term memory (STM) compared with non-musicians [48]. The observed simple association with verbal STM disappeared after the researchers accounted for non-verbal intelligence, executive updating, age and socio-economic status (see also [35]). Another multi-lab study failed to replicate previously reported associations between music training and the neural auditory encoding of speech syllables [49].

Our results provide converging evidence for the hypothesis that general auditory skills underlie reported associations between musical expertise and L2 outcomes. For example, Kempe *et al.* [50] found that low-level auditory discrimination contributes to the link between musical expertise (i.e. training or ability) and the discrimination of speech sounds from a novel L2. Similarly, when Zu and Choi [51] asked Cantonese-speaking adults to discriminate Thai syllables differing in lexical tones, vowels, or consonants, associations with music training disappeared after controlling for auditory thresholds—the minimum difference between tones that listeners could detect reliably. Other findings confirm that auditory thresholds predict performance on tests of musical ability even after accounting for music training [28] and that musical ability predicts subsequent music training better than training predicts ability [52]. In one instance, neither music training nor musical ability predicted adults' ability to recognize emotions from speech prosody when auditory thresholds (particularly pitch discrimination) were held constant [40]. In short, basic listening skills may form a common foundation for speech and music perception, which gives rise to an association that can be misinterpreted as causation [53]. Although 'speech and music are fundamental forms of human communication … that both rely heavily on auditory learning' [16, p. 98], observed associations do not necessitate a role for plasticity or cross-domain transfer.

Our findings suggest that theories of links between music and language need to specify which aspects of language ability are associated with musical expertise. They also have specific ramifications for existing theoretical perspectives. Although rhythm perception was relatively independent of other measures of musical expertise (music training and self-reports of musical ability) in both studies, it showed no special association with L2 proficiency. In one instance (L2-reading, Study 2), the data provided substantial evidence for the null hypothesis. A special role for rhythm may be evident primarily among atypical populations, when temporal processing is poor (e.g. [1]), or when rhythm is compared directly with melody (e.g. [25]). For example, Swaminathan & Schellenberg [11] found that rhythm perception and musical memory predicted children's language abilities (i.e. speech or grammar), but melody perception did not. Moreover, in a four-month longitudinal intervention with pre-schoolers, improvements in phonological awareness were evident after training in pitch (melody) but not after training in rhythm [54]. Other perspectives, such as the MAPLE framework [12] and the OPERA hypothesis [14], suggest broad links between musical expertise and language, with OPERA positing a causal role for music training. Here, we found limited evidence for associations between musical expertise and the ability to use L2 in context, and tests of associations with music training consistently favoured the null hypothesis.

In sum, across two large samples, we found little evidence that musical expertise was associated with L2 proficiency as measured by self-reports or objective tests of pragmatic competence. To date, most of the reported associations have involved L2 phonology and could stem from basic auditory skills. Individual differences in musical expertise may predict sensitivity to fine-grained distinctions in L2 speech sounds,

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which is an important component of L2 ability. Our findings suggest, however, that musical expertise has little relevance for the ability to use L2 in context.

Ethics. Approval for the research protocol for Studies 1 and 2 was obtained from the local ethics committee at Iscte, University Institute of Lisbon (reference 07/2021).

Data accessibility. The stimuli and procedures are available online (https://app.gorilla.sc/openmaterials/218554), as are the data [55].

Supplementary material is available online [56].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Author's contributions. E.G.S.: conceptualization, formal analysis, funding acquisition, methodology, supervision, writing—original draft, writing—review and editing; A.I.C.: conceptualization, data curation, formal analysis, methodology, writing—review and editing; J.S.: data curation, investigation, methodology; C.F.L.: conceptualization, investigation, methodology, project administration, supervision, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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