Reexamining the Effects of Ratio Simplicity and Familiarity on Abstract Pattern Learning in Dyad Sequences

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ABSTRACT: In this study, we conceptually replicated two experiments by Crespo-Bojorque and Toro (2016; Experiments 4a & 5a) in an attempt to corroborate their finding of improved performance in abstract pattern learning within sequences of conventionally consonant versus dissonant dyads. In addition, to determine whether the processing advantages for consonance that they reported were due to the ratio simplicity or the familiarity of the stimuli, we added a condition in which participants were either presented with unconventionally tuned small versus large integer-ratio dyads. Results failed to replicate Crespo-Bojorque and Toro's (2016) original findings: Neither conventionally consonant nor unconventionally tuned small integer-ratio dyads conferred any advantage in pattern learning or generalization. However, in a post hoc analysis using a subsample of participants with no music training, there was evidence that initial pattern learning was more efficient when the patterns were embedded within familiar as opposed to unconventionally tuned dyads. This is consistent with Crespo-Bojorque and Toro's (2016) proposition that interval familiarity may bolster abstract pattern detection. Discussion centers on the need for additional research on the impact of consonance on pattern learning, highlighting the importance of adjudicating between the effects of ratio simplicity and enculturation.

Submitted 2021 July 18; accepted 2021 October 19.
Published 2023 August 10; https://doi.org/10.18061/emr.v17i1.8446

KEYWORDS: *consonance, intervals, ratios, familiarity, unconventional tuning*

WITHIN Western music theory, dyads formed by simultaneously sounded pairs of tones have traditionally been categorized as either "consonant" or "dissonant" (Whittall, 2011). Conventionally consonant dyads, such as the octave (P8), perfect 4th (P4) and perfect 5th (P5), appear with great frequency in the harmonies comprising a variety of Western musical styles and, correspondingly, tend to be subjectively rated as more pleasant (Parncutt & Hair, 2011). In contrast, dissonant dyads, including the minor 2nd (m2), tritone (TT), and major 7th (M7) appear more sparsely in Western music, largely serving to create "tension" associated with an expectation and/or desire to return to consonant sonorities (Margulis, 2005). Subjectively, such dyads tend to be perceived as relatively unpleasant. Explanations for the appeal and prevalence of conventionally consonant dyads have focused on their physical properties in isolation. For instance, it has been proposed that consonant dyads are easier to process and thereby preferred, because they are based on small integer frequency ratios (e.g., Schellenberg & Trehub, 1996), because their partials more closely resemble the harmonic series characterizing voiced speech sounds (e.g., Bowling et al., 2018), and/or because they are "smoother", featuring overtones that are far enough apart in frequency to minimize cochlear interference (Helmholtz, 1877/1912; see Harrison & Pearce, 2020, for a comprehensive review).

Recent work by Crespo-Bojorque and Toro (2016) points to the possibility of another, more holistic means by which a preference for consonant sonorities may arise. They propose that abstract harmonic patterns may be easier to encode and generalize when they are composed of conventionally consonant versus dissonant intervals. If so, given that music is essentially a "demanding pattern detection task" (Crespo-Bojorque & Toro, 2016, p. 99), consonant chords may come to be favored by musicians and listeners alike, not only due to their individual physical properties, but because they *collectively* facilitate the processing of musical structure over time.

According to Crespo-Bojorque and Toro (2016), there are at least two distinct processes by which the use of conventionally consonant versus dissonant chords might facilitate the detection of abstract harmonic patterns. First, since conventionally consonant, relative to dissonant, dyads are generated using small integer frequency ratios (e.g., 3/2 for the P5 versus 45/32 for the TT) or at least close approximations of such ratios, they may serve as "reference points for perception" (cf. Rosch, 1975). This implies that conventionally consonant dyads should be more likely to capture attention, perhaps due to the simplicity of their patterns of vibration on the basilar membrane (Schellenburg & Trehub, 1996). As such, they should be more readily encoded and recognized, making it easier to detect when they have been altered (Schellenberg & Trehub, 1994). In addition, they should be relatively likely to function as "natural prototypes" (Rosch, 1973) by comparison to which other sonorities may be categorized (Schellenberg & Trehub, 1996).

Crespo-Bojorque and Toro (2016) propose that these processing advantages associated with small integer frequency ratios may ease the cognitive burden inherent in detecting abstract patterns involving conventionally consonant intervals. However, they also recognize that superior performance in pattern detection involving consonant dyads may result not from their intrinsic ratio simplicity, but rather, from their cultural familiarity. As demonstrated by McLachlan et al. (2013), the precision of pitch estimation for the tones comprising a musical interval improves with exposure, gradually leading the interval to be experienced as more pleasant. Theoretically speaking, this advantage in pitch processing may convey benefits in terms of abstract pattern detection involving familiar chords, even if the latter are comprised of relatively complex, large integer frequency ratios.

To adjudicate between these possibilities and provide a strong initial test of whether abstract patterns are more readily detected when embedded within conventionally consonant chord sequences, Crespo-Bojorque and Toro (2016) first conducted a series of studies using rats that had been raised in a music-free environment. Earlier research had shown that rats are capable of detecting abstract patterns within sequences of acoustic stimuli (de la Mora & Toro, 2013). Crespo-Bojorque and Toro (2016) reasoned that if rats' learning was enhanced when these sequences were composed of consonant versus dissonant dyads, this would offer compelling evidence that consonance confers an advantage in pattern detection and that this benefit is linked to the intrinsic features of consonant intervals (i.e., their ratio simplicity) as opposed to their familiarity. However, whereas Crespo-Bojorque and Toro (2016) did find that rats were able to learn patterns within the musical stimuli to which they were exposed—specifically, to discriminate between sequences involving a repeated dyad versus no repetition—they found no evidence that pattern learning was more efficient or better generalized when the stimuli were conventionally consonant.

In light of these null results, Crespo-Bojorque and Toro (2016) next conducted a series of conceptual replication studies with human participants. Here, during the training block, participants were presented with sequences of three dyads and asked to press a key only after "correct" sequences appeared (i.e., a go/no-go procedure). Feedback regarding which sequences were correct was provided after each key press. In the experiments of most relevance to the current study, sequences were either composed of conventionally consonant dyads or dissonant dyads. Moreover, depending on the experiment, the correct sequences included patterns that featured either immediate (AAB) or delayed (ABA) repetition of a dyad whereas incorrect sequences involved no repetition (ABC). After successful training, at which point participants could reliably perform the task without errors, a generalization block was administered in which participants were given pairs of three-dyad sequences in a two-alternative forced choice (2AFC) procedure. On each trial, participants were presented with a previously unheard sequence of dyads that shared the same pattern as that heard during the training block (i.e., AAB or ABA) as well as a sequence of "new" dyads that shared the "incorrect" pattern from that block (i.e., ABC). They were asked to select the sequence that was most similar to the correct stimuli heard during the training phase. In the experiments at issue, the same type of stimulus (consonant versus dissonant) was used in both the training and test blocks. Results showed no reliable difference between groups in terms of the number of trials required to learn the correct dyad pattern during the training block; however, participants who heard consonant, relative to dissonant, dyads showed significantly better 2AFC test performance, suggesting that they were more capable of generalizing the learned pattern to a new set of stimuli. (Effect sizes for the latter findings were reported as *d* = .50 for the "AAB" experiments and *d* = .55 for the "ABA" experiments, suggesting "medium" effects according to Cohen's [1988] benchmarks).

These results are consistent with Crespo-Bojorque and Toro's (2016) hypothesis that consonance facilitates abstract pattern detection. However, given that the findings were obtained with human participants, who have presumably had considerable experience listening to music, the procedure was incapable of determining whether the consonance-related advantage was due to the ratio simplicity of the dyads or their familiarity. In the present study, we aimed to rectify this confound by expanding upon their procedure. Specifically, we replicated two of their experiments involving conventionally consonant versus dissonant dyads, yet also added a new experimental condition in which participants were exposed to unconventionally tuned dyads that do not appear in Western music. Within this condition, we additionally assigned some participants to be administered stimuli generated from small integer frequency ratios, whereas others were administered stimuli generated from ratios made up of relatively large integers. In this way, we hoped to replicate Crespo-Bojorque and Toro's (2016) key findings with humans, while also potentially adjudicating between the two competing process models they proposed: If individuals showed an advantage in pattern learning for both conventional as well as unconventional small integer-ratio dyads, this would support the notion that the processing advantages for consonance that they found were associated with ratio simplicity as opposed to familiarity.

METHOD

Participants

Participants were 238 undergraduate students at the University at Albany (104 male; 131 female; 3 unknown; Age: *M* = 19.18, *SD* = 1.61) who completed the study for course credit in an introductory psychology course. The average sample size per cell (59.5) was approximately 36% larger than that (38) employed by Crespo-Bojorque and Toro (2016). One hundred fifty-six (65%) participants reported having less than one year of formal training in music theory and one hundred five (44%) reported less than one year of formal training on a musical instrument. Research ethics committee approval for use of human subjects in this experiment was granted by the Institutional Review Board of the University at Albany.

Materials

All experimental stimuli were composed of sequences of three dyads. Dyads were played in a piano timbre and each had a bass note fixed at C4 (261.63 Hz). These stimuli were created from single-note piano samples from the University of Iowa's Electronic Music Studios digital archive (Fritts, 2019). Specifically, the bass note sample (C4) was combined with higher pitch samples in Audacity (v. 2.4.2) to create the 24 distinct dyads used in this study.

In the Conventional Tuning condition, the dyads were exactly the same as those used by Crespo-Bojorque and Toro (2016; Experiments 4a & 5a). Here, one group of participants was randomly assigned to hear the same conventionally consonant sequences administered in Experiment 4a of Crespo-Bojorque and Toro's study (2016). These comprised different combinations of the octave, P4, and P5 during the training block and different combinations of the minor 3rd (m3), major 3rd (M3), and major 6th (M6) during the test block. Correspondingly, another group of participants was randomly assigned to hear the same conventionally dissonant sequences administered in Experiment 5a of Crespo-Bojorque and Toro's study (2016). These comprised different combinations of the m2, TT, and minor 9th (m9) during the training block and different combinations of the major 2nd (M2), minor 7th (m7), and M7 during the test block. Following Crespo-Bojorque and Toro (2016), conventional dyads were tuned using 12 tone equal temperament (12-TET), such that consonant stimuli approximated small integer frequency ratios and dissonant stimuli approximated larger integer frequency ratios (see Table 1).

Table 1. Intervals used During Training and Test (Conventional Dyad Conditions)

	Small Integer Ratio (Consonant) Intervals				Large Integer Ratio (Dissonant) Intervals			
	Dyad	Ratio	Freq (Hz)	Cents	Dyad	Ratio	Freq (Hz)	Cents
Training	P4	4:3	349.23	500	m2	16:15	277.18	100
	P5	3:2	392.00	700	TT	45:32	369.99	600
	P8	2:1	523.25	1200	m9	15:32	554.37	1300
Test	m3	6:5	311.13	300	M2	9:8	293.66	200
	M3	5:4	329.63	400	m7	16:9	466.16	1000
	M6	5:3	440.00	900	M7	15:8	493.88	1100

Note: All dyads had a bass note of 261.63Hz (C4), therefore values in the "Freq" column correspond to the frequencies (Hz) of the remaining tones added to the bass note to create each dyad. Ratios are approximate.

In the newly appended Unconventional Tuning condition, participants were randomly assigned to hear sequences of dyads that departed to varying degrees from the familiar 12-TET tuning system and that appear in alternative systems such as Bohlen-Pierce just intonation (Loy, 2006). The higher pitches added to the bass note to create these dyads were pitch-shifted to the appropriate non-12-TET frequency values using Audacity's "Change Pitch" function prior to pitch combination (see Table 2). To ensure a strong test of the effect of ratio simplicity, in one group, participants heard combinations of dyads precisely generated from relatively small integer frequency ratios. Here, during the training block, they were exposed to dyads based on ratios of 7/6, 9/7, and 9/5, whereas during the test block, they heard dyads based on ratios of 7/5, 5/3, and 7/3. In contrast, participants in a separate group heard combinations of dyads generated from relatively large integer frequency ratios. Specifically, during the training block, they were exposed to dyads based on ratios of 147/125, 75/49, and 15/7, whereas during the test block, they heard dyads based on ratios of 27/25, 21/16, and 25/9 (see Table 2).

Table 2. *Intervals used During Training and Test (Unconventional Dyad Conditions)*

	Small Integer Ratio Intervals				Large Integer Ratio Intervals			
	Ratio	Freq (Hz)	Cents	Dist (c)	Ratio	Freq (Hz)	Cents	Dist (c)
Training	7:6	305.24	266.87	33.06	147:125	307.68	280.67	19.28
	9:7	336.38	435.08	35.10	75:49	400.45	736.93	36.94
	9:5	470.93	1017.60	17.61	15:7	560.64	1319.44	19.48
Test	7:5	366.28	582.51	17.46	27:25	282.56	133.24	33.26
	5:3	436.05	884.36	15.60	21:16	343.39	470.78	17.06
	7:3	610.47	1466.87	33.09	25:9	726.25	1768.72	8.55

Note: All dyads had a bass note of 261.63Hz (C4), therefore values in the "Freq" column correspond to the frequencies (Hz) of the remaining tones added to the bass note to create each dyad; "Dist" = absolute difference in cents (c) between the upper tone of each unconventional dyad and that of the closest conventional (12-TET) tone.

Following Crespo-Bojorque and Toro (2016; Experiments 4a & 5a), dyads in all conditions were grouped into either "correct" sequences, forming an AAB pattern (e.g., P4-P4-P5), or "incorrect" sequences (e.g., P4-P5-P8), forming an ABC pattern. Lists of correct and incorrect sequences used in the training and test blocks appear in Tables 3 and 4. Each dyad sequence was 2000 ms long with no interstimulus interval between the three constituent dyads. These sequences were RMS-equated in PRAAT (v. 6.0.43; Boersma & Weenink, 2018) prior to their inclusion in the experimental procedure outlined below.

Table 3. *Interval Sequences used in Training and Test in the Conventional Dyad Conditions*

	Small Integer Ratio		Large Integer Ratio	
	AAB	ABC	AAB	ABC
Training	P8--P8--P5	P8--P5--P4	m9--m9--TT	m9--TT--m2
	P8--P8--P4	P8--P4--P5	m9--m9--m2	m9--m2--TT
	P5--P5--P8	P5--P8--P4	TT--TT--m9	TT--m9--m2
	P5--P5--P4	P5--P4--P8	TT--TT--m2	TT--m2--m9
	P4--P4--P8	P4--P8--P5	m2--m2--m9	m2--m9--TT
	P4--P4--P5	P4--P5--P8	m2--m2--TT	m2--TT--m9
Test	m3--m3--M3	m3--M3--M6	M2--M2--m7	M2--m7--M7
	m3--m3--M6	M3--m3--M6	M2--M2--M7	m7--M2--M7
	M3--M3--m3	m3--M6--M3	m7--m7--M2	M2--M7--m7
	M3--M3--M6	M3--M6--m3	m7--m7--M7	m7--M7--M2
	M6--M6--m3	M6--M3--m3	M7--M7--M2	M7--m7--M2
	M6--M6--M3	M6--m3--M3	M7--M7--m7	M7--M2--m7

Table 4. *Interval Sequences used in Training and Test in the Unconventional Dyad Conditions*

	Small Integer Ratio		Large Integer Ratio	
	AAB	ABC	AAB	ABC
Training	9:5--9:5--9:7	9:5--9:7--7:6	15:7--15:7--75:49	15:7--75:49--147:125
	9:5--9:5--7:6	9:5--7:6--9:7	15:7--15:7--147:125	15:7--147:125--75:49
	9:7--9:7--9:5	9:7--9:5--7:6	75:49--75:49--15:7	75:49--15:7--147:125
	9:7--9:7--7:6	9:7--7:6--9:5	75:49--75:49--147:125	75:49--147:125--15:7
	7:6--7:6--9:5	7:6--9:5--9:7	147:125--147:125--15:7	147:125--15:7--75:49
	7:6--7:6--9:7	7:6--9:7--9:5	147:125--147:125--75:49	147:125--75:49--15:7
Test	7:5--7:5--5:3	7:5--5:3--7:3	27:25--27:25--21:16	27:25--21:16--25:9
	7:5--7:5--7:3	5:3--7:5--7:3	27:25--27:25--25:9	21:16--27:25--25:9
	5:3--5:3--7:5	7:5--7:3--5:3	21:16--21:16--27:25	27:25--25:9--21:16
	5:3--5:3--7:3	5:3--7:3--7:5	21:16--21:16--25:9	21:16--25:9--27:25
	7:3--7:3--7:5	7:3--5:3--7:5	25:9--25:9--27:25	25:9--21:16--27:25
	7:3--7:3--5:3	7:3--7:5--5:3	25:9--25:9--21:16	25:9--27:25--21:16

Procedure

Due to the Covid-19 crisis of 2020, the entire procedure was run online using PsyToolKit software (Stoet, 2010; 2017). Participants were instructed to use headphones when completing the study and were required to use a device with a physical keyboard as opposed to a touchscreen. Replicating the procedure of Crespo-Bojorque and Toro (2016), the experiment involved two phases, a training block followed by a test block. As alluded to earlier, the training phase involved a go/no-go procedure in which training sequences were presented one after the other, with the stipulation that no more than two sequences of the same type (i.e., AAB versus ABC) could appear consecutively.

Participants were told that they would hear sequences of musical chords (“combinations of notes”) and that each sequence would include three chords. Some of these sequences would be “correct” and others “incorrect” and that to find out which sequences were which, they were to press the spacebar immediately after hearing each sequence. Finally, they were told, and then reminded immediately before the block began, that they should try to press the spacebar only after correct sequences. Whenever participants pressed the spacebar, they received feedback on screen notifying them that they were either "correct" or "incorrect". In addition, if they failed to press the spacebar on a correct trial, they received a message informing them that they should have pressed the spacebar, but did not.

After participants completed a minimum of 30 go/no-go trials and additionally tendered three correct responses in a row, the training block ended and the test block immediately began. There was no upper limit set as to the number of trials; however, all participants successfully attained the aforementioned performance threshold and were able to proceed to the test block. As noted above, this block involved a 2AFC procedure meant to assess participants' ability to generalize the "correct" pattern that they had learned in the first block to a new set of dyad sequences. Participants were instructed that in this next part of the study, they would hear pairs of chord sequences, one after the other and that they were to indicate which sequence was most similar to the "correct" sequences that they heard earlier. They were instructed to press the "A" key to indicate "Sequence 1" and the "L" key to indicate "Sequence 2". At this point, they were administered 12 2AFC trials. On each of these trials they heard two consecutive test sequences, one "correct" (AAB) and one "incorrect" (ABC), with the order of sequence types evenly counterbalanced across trials. Trials were separated by a silent interval of 2000 ms.

After completing the experiment, participants were administered measures of demographics including age and gender as well as the music training subscale of the Goldsmiths Musical Sophistication Index (GMSI; Müllensiefen et al., 2014). They were then fully debriefed regarding the purposes of the study.

RESULTS

The number of trials to reach criterion within the training block and the percentage of correct responses tendered during the test block (i.e., percentage of choices of the target AAB pattern) are reported in Table 5. As a first step in the analysis, we computed a 2 (Tuning: Conventional vs. Unconventional) X 2 (Ratio: Small vs. Large Integer) ANOVA on trials to criterion. This revealed no significant effects (all *p*s > .14). As a supplementary procedure, we also computed Bayes factors (BFs) for the main and interactive effects of Tuning and Ratio. All BFs were less than 1, with the best model (which only included Tuning) suggesting 2.4:1 evidence in favor of the null hypothesis. A second ANOVA on percentage of "correct" responses likewise revealed no significant effects of either Tuning or Ratio (all *p*s > .65). All BFs were again less than 1, with the best model (again, including Tuning alone), suggesting 6.4:1 evidence in favor of the null. As such, there was no evidence that either ratio simplicity or dyadic familiarity influenced either the efficiency with which participants initially learned the target pattern or their ability to generalize this pattern to new dyad sequences. The latter result fails to conceptually or constructively replicate the main findings of Crespo-Bojorque and Toro (2016).

Table 5. *Descriptive Statistics for Performance on the Training and Test Blocks, Indexed by Condition*

Condition	Trials		PCT	
	M	*SD*	*M*	*SD*
Low Integer Ratio Conventional	41.63	19.70	73.98	22.55
High Integer Ratio Conventional	41.89	19.69	72.18	21.86
Low Integer Ratio Unconventional	44.76	23.62	74.09	20.58
High Integer Ratio Unconventional	47.47	27.63	74.48	19.12

Note: "Trials" = number of trials to reach criterion within the training phase; "PCT" = percentage of "correct" responses during the 12 test trials (i.e., percentage of choices of the target AAB pattern).

In an attempt to account for the discrepancy between our findings and those of the original study, we noted that Crespo-Bojorque and Toro (2016) had described their participants as having received "no formal musical training". Whereas participants in our sample were selected from an introductory psychology subject pool and a great many received no training at all (see *Participants*), most did report at least six months of training. Although Crespo-Bojorque and Toro (2016) did not posit that music training should moderate their effects, to potentially equate our samples more closely, we recomputed our analyses on the subset of 91 participants who reported absolutely no formal instrumental or vocal training on the GMSI. The number of trials to reach criterion and the percentage of correct responses for this subset of participants are reported in Table 6. Post hoc analyses revealed no main or interactive effects involving Ratio (*p*s > .32). However, the analysis did reveal a significant main effect of Tuning on trials to completion, $F(1, 87) = 6.16$, $p < .02$, $\eta^2 = .07$, reflecting that participants who were administered unconventionally tuned dyads (n = 41) required more trials to learn the target pattern (n = 41; $M = 49.76$; $SD = 28.62$) than did participants who were administered conventionally tuned dyads (n = 50; $M = 37.66$; $SD = 9.67$). The BF for this effect suggested 3.95:1 evidence in its favor relative to the null, weakly positive evidence according to the standards of Kass and Raftery (1995). Upon reexamination of Crespo-Bojorque and Toro's (2016) original findings, this is consistent with a nominal, albeit nonsignificant trend for individuals to take longer to learn the target pattern with (presumably less familiar) dissonant dyads. To confirm, even among participants in this training-free subsample, there was no evidence for effects of either Tuning or Ratio (all BFs < 1) on percentage of "correct" responses, failing to replicate Crespo-Bojorque and Toro's (2016) main findings regarding pattern generalization.

Table 6. *Descriptive Statistics for Performance on the Training and Test Blocks (No Music Training)*

Condition	Trials		PCT	
	M	*SD*	*M*	*SD*
Low Integer Ratio Conventional	36.79	10.15	67.10	22.65
High Integer Ratio Conventional	38.41	9.40	74.62	21.28
Low Integer Ratio Unconventional	45.41	21.47	72.35	19.98
High Integer Ratio Unconventional	53.18	33.17	75.59	19.50

Note: "Trials" = number of trials to reach criterion within the training phase; "PCT" = percentage of "correct" responses during the 12 test trials (i.e., percentage of choices of the target AAB pattern).

DISCUSSION

In this study, we conceptually replicated two recent experiments by Crespo-Bojorque and Toro (2016) in an attempt to corroborate their finding that individuals show improved performance in abstract pattern learning for sequences of conventionally consonant versus dissonant dyadic intervals. We also appended a new condition in which participants were either presented with unconventionally tuned small versus large integer ratio dyads to determine whether the processing advantages for consonance that they reported were due to the ratio simplicity or the familiarity of the dyad stimuli. Our results failed to replicate Crespo-Bojorque and Toro's (2016) findings: Neither conventionally consonant nor unconventionally tuned small integer ratio dyads conferred any advantage in pattern learning or generalization. In a post hoc analysis using a subsample of participants who lacked music training (making them presumably more akin to those in Crespo-Bojorque and Toro's [2016] original study), there was evidence that initial pattern learning was more efficient when the patterns were embedded within familiar (12-TET) as opposed to unconventionally tuned dyads. This is consistent with Crespo-Bojorque and Toro's (2016) contention that abstract patterns may be better learned across consonant dyads due to their familiarity. However, it bears repeating that this effect was not statistically significant in their own prior study and was only obtained at present using a subsample selected using post hoc criteria. Moreover, from a theoretical standpoint, it is unclear why any effect of dyad familiarity on abstract pattern learning would be limited to individuals with absolutely no music training. Upon consideration, it is possible that individuals with more extensive music training may have greater exposure to relatively uncommon intervals (Palmer & Griscom, 2013), diluting the difference in familiarity between conventionally and unconventionally tuned dyads. However, this remains entirely speculative and any conclusions must remain tentative pending replication of the effect at issue.

To be clear, the results of this study by no means suffice to disconfirm the original findings of Crespo-Bojorque and Toro (2016) nor their hypothesis regarding processing advantages for sequences of dyads that are either familiar or that feature "simple" frequency ratios. At minimum, there were a number of ostensibly superficial, but potentially important differences in the procedures (e.g., online vs. lab-based), sample (e.g., American vs. Spanish), and translations and formatting of instructions that may have contributed to our null results. It also should be noted that Crespo-Bojorque and Toro (2016) did conceptually replicate the findings in question using a slightly altered procedure (e.g., an ABA as opposed to AAB target pattern) in Experiments 4b and 5b of their study. As such, our results may simply suggest that the effect that they discovered is relatively sensitive to contextual variations and that additional research will be required to explore its boundary conditions. It is also possible that the effect is more subtle than their original findings would suggest, in which case it might be useful to include test blocks with a greater number of trials in future studies. As it stands, the inclusion of only 12 2AFC trials may have permitted participants who were unable to generalize the rule to nonetheless guess the "correct" response on several trials, inflating their performance and diminishing the ability of the task to detect performance differences due to ratio simplicity.

Whereas they fail to confirm the influence of ratio simplicity on abstract pattern learning, our results also by no means suggest that this variable, which has been central to historical conceptualizations of consonance and dissonance (see e.g., Bowling & Purves, 2015, for a review), does not influence the ease of harmonic processing. For instance, as alluded to earlier, several studies have found evidence that conventionally consonant dyads (which approximate small integer frequency ratios) serve as perceptual reference points, such that it is easier to detect changes to patterns involving such dyads (e.g., Schellenberg & Trehub, 1994; 1996). Notably, findings of this sort have even been obtained with infants, leading Schellenberg and Trehub (1996) to propose that small integer ratios represent "natural musical intervals" that innately confer perceptual advantages. However, such developmental studies cannot entirely rule out effects of early music listening experience, including exposure *in utero*. Moreover, Schellenberg and Trehub's (1996) proposition is very much at odds with that recently enunciated by Parncutt and Hair (2018), who argue that it is "fundamentally incorrect" (p. 475) to conceptualize musical intervals as ratios, that there is little evidence that they are represented as such in the brain, and that all musical intervals are instead "learned, approximate, perceptual distances" (p. 491). This controversy points to the need for additional studies explicitly aimed at teasing apart the effects of ratio simplicity and enculturation on interval processing.

In conclusion, the results of our study suggest that the influence of consonance on abstract pattern learning reported by Crespo-Bojorque and Toro (2016) may be limited in its reliability and generalizability. However, given the importance of Crespo-Bojorque and Toro's (2016) hypothesis, which suggests a novel, holistic means by which chords may gain prevalence within a particular musical culture, additional empirical investigation based on their work is clearly warranted. We hope that the present constructive replication study will help set the stage for additional research along these lines and more broadly contribute to building cumulative knowledge regarding the origins and impact of musical consonance.

ACKNOWLEDGEMENTS

We are grateful to Dr. Juan M. Toro for helping us clarify details of the original procedure of Crespo-Bojorque and Toro (2016; Experiments 4a & 5a). This article was copy edited and layout edited by Jonathan Tang.

NOTES

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REFERENCES

Audacity Team (2021). *Audacity(R): Free audio editor and recorder* [Computer application]. Version 2.4.2 retrieved January 1st 2021 from https://audacityteam.org/

Boersma, P. & Weenink, D. (2018). *Praat: Doing phonetics by computer* [Computer software]. Version 6.0.43. Retrieved from http://www.praat.org

Bowling, D. L., & Purves, D. (2015). A biological rationale for musical consonance. *Proceedings of the National Academy of Sciences*, *112*, 11155–11160. https://doi.org/10.1073/pnas.1505768112

Bowling, D. L., Purves, D., & Gill, K. Z. (2018). Vocal similarity predicts the relative attraction of musical chords. *Proceedings of the National Academy of Sciences*, *115*, 216-221. https://doi.org/10.1073/pnas.1713206115

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Routledge Academic.

Crespo-Bojorque, P., & Toro, J. M. (2016). Processing advantages for consonance: A comparison between rats (Rattus norvegicus) and humans (Homo sapiens). *Journal of Comparative Psychology, 130*, 97–108. https://doi.org/10.1037/com0000027

de la Mora, D. M., & Toro, J. M. (2013). Rule learning over consonants and vowels in a non-human animal. *Cognition*, *126*, 307–312. https://doi.org/10.1016/j.cognition.2012.09.015

Fritts, L. (2019). Piano and clarinet samples. [Audio database]. *Musical instrument samples*. Retrieved from http://theremin.music.uiowa.edu/MIS.html#

Harrison, P. M. C., & Pearce, M. T. (2020). Simultaneous consonance in music perception and composition. *Psychological Review, 127*, 216-244. https://doi.org/10.1037/rev0000169

Helmholtz, H. (1877/1912). *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (4th ed.) *[On the sensations of tone as a physiological basis for the theory of music]*. (A. J. Ellis, Trans.). Longmans.

Kass, R., & Raftery, A. (1995). Bayes factors. *Journal of the American Statistical Association, 90*, 773-795. https://doi.org/10.1080/01621459.1995.10476572

Loy, G. (2006). *Musimathics — The mathematical foundations of music, Vol. 1*. MIT Press.

Margulis, E. (2005). A model of melodic expectation. *Music Perception: An Interdisciplinary Journal, 22*, 663-714. https://doi.org/10.1525/mp.2005.22.4.663

McLachlan, N., Marco, D., Light, M., & Wilson, S. (2013). Consonance and pitch. *Journal of Experimental Psychology: General*, *142*, 1142-1158. https://doi.org/10.1037/a0030830

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The musicality of non-musicians: An index for assessing musical sophistication in the general population. *PloS One*, *9*, e89642. https://doi.org/10.1371/journal.pone.0089642

Palmer, S. E., & Griscom, W. S. (2013). Accounting for taste: individual differences in preference for harmony. *Psychonomic Bulletin & Review*, *20*, 453–461. https://doi.org/10.3758/s13423-012-0355-2

Parncutt, R., & Hair, G. (2011). Consonance and dissonance in music theory and psychology: Disentangling dissonant dichotomies. *Journal of Interdisciplinary Music Studies*, *5*, 119–166. https://doi.org/10.4407/jims.2011.11.002

Parncutt, R., & Hair, G. (2018). A psychocultural theory of musical interval: Bye bye Pythagoras. *Music Perception, 35*, 475–501. https://doi.org/10.1525/mp.2018.35.4.475

Rosch, E. H. (1973). Natural categories. *Cognitive Psychology, 4*, 328–350. https://doi.org/10.1016/0010-0285(73)90017-0

Rosch, E. (1975). Cognitive reference points. *Cognitive Psychology, 7*, 532–547. https://doi.org/10.1016/0010-0285(75)90021-3

Schellenberg, E. G., & Trehub, S. E. (1994). Frequency ratios and the perception of tone patterns. *Psychonomic Bulletin & Review, 1*, 191–201. https://doi.org/10.3758/BF03200773

Schellenberg, E., & Trehub, S. (1996). Natural musical intervals: Evidence from infant listeners. *Psychological Science*, *7*, 272-277. https://doi.org/10.1111/j.1467-9280.1996.tb00373.x

Stoet G. (2010). PsyToolkit: a software package for programming psychological experiments using Linux. *Behavior Research Methods*, *42*, 1096–1104. https://doi.org/10.3758/BRM.42.4.1096

Stoet, G. (2017). PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teaching of Psychology, 44*, 24–31. https://doi.org/10.1177/0098628316677643

Whittall, A. (2011). Consonance and dissonance. In *The Oxford companion to music*. Retrieved July 17, 2021, from https://www.oxfordreference.com/view/10.1093/acref/9780199579037.001.0001/acref-9780199579037-e-1581?rskey=dtWwrC&result=1