Processing advantages for consonance: A comparison between rats (*Rattus norvegicus)* and humans (*Homo sapiens)*

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Abstract

Consonance is a salient perceptual feature in harmonic music associated with pleasantness. Besides being deeply rooted in how we experience music, research suggests consonant intervals are more easily processed than dissonant intervals. In the present work we explore from a comparative perspective if such processing advantage extends to more complex tasks such as the detection of abstract rules. We ran experiments on rule learning over consonant and dissonant intervals with non-human animals and human participants. Results show differences across species regarding the extent to which they benefit from differences in consonance. Animals learn abstract rules with the same ease independently of whether they are implemented over consonant intervals (Experiment 1), dissonant intervals (Experiment 2), or over a combination of them (Experiment 3). Humans, on the contrary, learn an abstract rule better when it is implemented over consonant (Experiment 4) than over dissonant intervals (Experiment 5). Moreover, their performance improves when there is a mapping between abstract categories defining a rule and consonant and dissonant intervals (Experiments 6 and 7). Results suggest that for humans, consonance might be used as a perceptual anchor for other cognitive processes as to facilitate the detection of abstract patterns. Lacking extensive experience with harmonic stimuli, non-human animals tested here do not seem to benefit from a processing advantage for consonant intervals.

Keywords

Introduction

Consonance, a musical trait associated with pleasantness, is one of the primary perceptual aspects in music. Studies performed with different Western populations have reported

similar consonant raking judgments of tone combinations (Malmberg, 1918; Roberts, 1986) with some combinations consistently ranked as consonant (pleasant; e.g., the perfect fifth) and other combinations consistently ranked as dissonant (unpleasant; e.g., the minor second). Early attempts to understand why some intervals are typically perceived as more pleasant than others focused on the physical properties of the sound. For instance, Pythagoras attributed consonance to small ratios between the tones in a musical interval, and Helmholtz (1877) correlated it to the roughness produced by the number of beats in an interval.

Besides aesthetic and physical differences, the distinction between consonance and dissonance also seems to involve at least some processing differences. Both adults and infants appear to have a processing advantage for consonant over dissonant intervals; they find it easier to detect changes over the former than over the latter (Schellenberg & Trehub, 1994; 1996). Such advantage could emerge if intervals with small ratios (consonant intervals) are being used as reference points for perception (Schellenberg & Trehub, 1994). Similar results were found in a recent study by Komeilipoor, Rodger, Craig and Cesari (2015) which showed that performance in a movement synchronization task is more accurate after the presentation of consonant sounds than after the presentation of dissonant sounds.

A growing body of literature has focused on the role that experience with specific stimuli might play in the emergence of consonance perception (e.g., McLachlan, Marco, Light & Wilson, 2013; Plantinga & Trehub, 2013). Results from these studies bring support to the idea that exposure to harmonic melodies plays a key role in the development of the observed preferences for consonant intervals. Thus, more research is needed to disentangle the relative contribution of the physical features of musical intervals from prolonged experience with a given musical system in determining the consonance or dissonance of a sound as interpreted by an individual. McLachlan and collaborators (2013) showed that familiarity with chords facilitates pitch processing, which in turn, increases the perception of a sound as consonant. Their findings lead to the conclusion that mechanisms involved in the identification of familiar sounds are at the basis of consonance judgments. Plantinga and Trehub (2013) observed that infants did not show preference for consonant stimuli after they had short-term exposure to both consonant and dissonant stimuli. The authors concluded that their results highlight the role of familiarity as the basis of consonance perception.

In the present study we wanted to shed some light on this issue from a comparative perspective. To do this, we took advantage of the lack of extensive experience producing and processing harmonic stimuli certain species have, and explored whether the processing advantage observed for consonant over dissonant intervals in humans could extend to other species. We used the rat as an experimental model. Rats are not a vocal learning species and they have no prolonged experience producing or processing harmonic stimuli. In addition, the rats used in the present study were raised in a controlled environment and were not exposed to any kind of musical stimuli before the experiments began. Thus, for the animals used in our experiments, consonant intervals differed from dissonant intervals in the relative size of the interval ratios defining them, but did not differ in their familiarity. Findings with this species regarding processing differences between consonance and dissonance could help to disambiguate the role of familiarity from the role of physical features.

Although the faculty for music has only been observed in humans, the perception of some of its fundamental components has also been explored across species (for a review see Hoeschele, Merchant, Kikuchi, Hattori & ten Cate, 2015).

Comparative research on consonance perception has shown that several avian species such as European Starlings (*Sturnus vulgaris*; Hulse, Bernard, & Braaten, 1995), black-capped chickadees (*Poecile atricapillus*; Hoeschele, Cook, Guillette, Brooks, & Sturdy, 2012), Java sparrows (*Padda oryzivora*; Watanabe, Uozumi, & Tanaka, 2005), pigeons (*Columbia livia*; Brooks & Cook, 2009) and primates such as Japanese monkeys (*Macaca fuscata*; Izumi, 2000) have the capacity to discriminate among chords based on sensory consonance. We have recently demonstrated that rats are able to discriminate consonant from dissonant intervals. However, they failed to generalize such discrimination to items played in new octaves not used during training (Crespo-Bojorque & Toro, 2015). The successful discrimination observed in rats suggests that at least some components of auditory processing needed to tell apart chords based on interval ratios are shared with rodent species.

We thus want to move beyond simple perceptual experiments and explore whether a processing advantage for consonance over dissonance can be observed in a demanding pattern detection task across species. Humans and non-human animals detect patterns even from early stages of development. This ability is key for tasks in which the learner needs to discover structures over complex signals, such as during music processing and language acquisition (e.g., Koelsch, Rohrmeier, Torrecuso & Jentschke, 2013). A well-studied case of discovery of abstract structures in acoustic stimuli is that of rule learning. Marcus, Vijayan, Bandi Rao and Vishton (1999) demonstrated that seven-month-old infants are able to learn simple abstract rules instantiated over nonsense words. In their experiments, the authors familiarized infants with a series of nonsense words that followed one pattern such as ABA (e.g. "gatiga") or AAB (e.g. "gatiti"), and tested them with new words that followed or did not follow the same pattern. The authors found that the infants could generalize the rule defining the words to new items presented during test. This demonstrated that, from an early age, infants have the ability to learn token-independent rules that might be fundamental for learning grammatical aspects of their language. Further experiments demonstrated that this ability could also be observed in the visual domain as long as the participants are presented with highly familiar objects (such as the pictures of dogs and cats; Saffran, Pollak, Seibel, & Shkolnik, 2007; see also Marcus, Fernandes & Johnson, 2007). Several studies have also shown that this ability is not specific to humans. Non-human animals seem to exhibit a capacity for detecting rules implemented over different kind of stimuli. Primates (rhesus monkeys [*Macaca mulata*]; Hauser & Glynn 2009), some birds (such as pigeons [*Columbia livia*]; Herbranson & Shimp, 2003; and European starlings [*Sturnus vulgaris*]; Genter, Fenn, Margoliash, & Nusbaum, 2006), and even rats (*Rattus norvegicus*; Murphy, Mondragón & Murphy, 2008; de la Mora & Toro, 2013) can detect abstract patterns in visual and acoustic sequences.

If the processing advantage described before for consonant intervals in humans extends to other species, we might find animals process sequences more accurately if they use consonant rather than dissonant intervals. To test this idea, first we explored whether rats, a species that does not have extensive experience producing or processing harmonic

vocalizations, and that reared in controlled environments does not have experience with Western harmonic music, might learn rules over consonant and dissonant intervals. Next, we tested human adults (living in a Western culture) with the same stimuli presented to rats. To compare how patterns are detected over consonant and over dissonant intervals by rats, we tested rule learning over the former (Experiment 1) and the latter (Experiment 2). More important for the present study, to explore the role that consonant and dissonant intervals might play as perceptual anchors, we mapped them to abstract categories defining a structure in Experiments 3. We then tested human participants on their ability to detect abstract rules implemented over consonant (Experiment 4) and dissonant intervals (Experiment 5), and whether contrasting consonance and dissonance would improve their structure extraction (Experiments 6 and 7).

Experiment 1: Rule learning over consonant intervals by rats

In the present experiment we explored rule extraction over consonant interval sequences in a non-human animal. We presented rats with a series of sequences composed of three consonant intervals that always followed an AAB pattern. To test for generalization, we presented them with new intervals not used during familiarization.

Subjects

Subjects were 19 female Long-Evans rats that were 5 months old. Rats were caged in pairs and were exposed to a 12-hr/12-hr light–dark cycle. Rats had water *ad libitum* and were food-deprived, maintained at 80 - 85% of their free-feeding weights. Food was delivered after each training session.

Stimuli

Stimuli were sequences of three consonant intervals. Intervals used during training were the octave (P8), the fifth (P5) and fourth (P4; see table 1). We chose to use these intervals because they are consistently rated as consonant in several experiments (e.g., Bidelman & Krishnan, 2009; Itoh, Miyazaki, & Nakada, 2003) and have been shown to be appropriately processed by non-human animals (McDermott & Hauser, 2004). There were two types of stimuli, target and non-target. Target stimuli followed an AAB pattern. The two first intervals of the sequence were the same and the third interval was different (e.g., octave-octave-fifth; see Figure 1). Non-target stimuli had three different intervals in a random sequence ABC (e.g., fifth-octave-fourth). There were 6 target (AAB) and 6 non-target sequences (ABC).

For the generalization test we created 12 novel stimuli (6 following an AAB pattern and 6 following an ABC sequence). Test stimuli were made from different intervals that were not used during training, including the minor third (m3), the major third (M3) and the major sixth (M6; see table 2). We used the grand piano setting of GarageBand software for Mac OS X to produce the stimuli. All the notes that composed the stimuli were created over the frequency range of 523.25–1109 Hz (C_5 to $C\#_6$). The hearing range of the rats is around 200 Hz up to 80 KHz (Heffner, Heffner, Contos, & Ott, 1994). Thus, stimuli presented during

both training and test fell within the hearing range of the animals. Each sequence of three intervals was 2 seconds long, with no silences between intervals in each sequence.

Apparatus

Rats were placed in Letica L830-C Skinner boxes (Panlab S. L., Barcelona, Spain) while custom-made software (RatBoxCBC) based on a PC computer controlled the stimuli presentations, recorded the lever-press responses, and provided reinforcement. A Pioneer A-445 stereo amplifier and two Electro-Voice S-40 loud- speakers (with a response range from 85 Hz to 20 kHz), located beside the boxes, were used to present the stimuli at 68 dB.

Procedure

The experiment consisted of a training phase and a test session. The training phase included 30 sessions, one session per day. In each training session, rats were placed individually in a Skinner box and were presented with 30 stimuli: 15 targets (AAB sequences) and 15 non-targets (ABC sequences). The stimuli were presented with an inter-stimulus interval of 60 sec. Stimulus presentation was balanced, so no more than two stimuli of the same type (AAB or ABC) would follow each other. Food reinforcement was delivered for lever pressing responses after each AAB stimulus. Rats did not receive food after the presentation of ABC stimuli, independently of lever presses. After the 30 sessions of the training phase, a generalization test was run. It was very similar to training sessions; however, eight test items replaced eight stimuli from the training list. The replacement of the stimuli was done in such way that, as in the training phase, there were no more than two stimuli of the same type following each other. Test stimuli were four new AAB and ABC sequences. The test sequences were composed of novel two-note intervals not presented during discrimination training. Importantly, rats did not receive food reward when the test stimuli were played regardless of whether or not they pressed the lever.

Results and discussion

We calculated the percentage of responses after target AAB stimuli out of the total number of responses to both AAB and ABC stimuli. A percentage higher than 50% indicates more lever pressing for AAB than for ABC stimuli. For the training phase, a repeated measures ANOVA was run with session (1-30) as the within-subject factor. The analysis showed a significant difference between sessions with an increase of responses to reinforced stimuli $F = (29, 522) = 19.6$, $p < .001$, $\eta_p^2 = .531$ (see Figure 2). For the test session, only data from test stimuli (8 test items) was analyzed. A one-sample t test showed that the mean percentage of responses to novel AAB sequences was significantly above what is expected by chance ($M = 60.0$, $SD = 7.15$), $t(18) = 33.5$, $p < .001$, 95% CI [56.6, 63.5], $d = 1.40$. These results indicate that rats learn and generalize rules implemented over consonant intervals.

Experiment 2: Rule learning over dissonant intervals by rats

In Experiment 2 we tested rats for rule learning over dissonant intervals. If consonance produces a processing advantage over dissonance in non-human animals, we should observe a decrease in performance when compared to the previous experiment. On the contrary, no

differences across experiments should be observed if the distinction between consonance and dissonance is not relevant for how these animals are processing acoustic stimuli.

Subjects

Twenty new female Long-Evans rats that were 5 months old were used.

Stimuli

The stimuli followed the same pattern as in Experiment 1 (AAB for target stimuli, and ABC random sequences composed of three different intervals for non-target stimuli). The only difference was that dissonant intervals were used for creating the sequences. For the training phase, we used the tritone (TT), the minor second (m2) and the minor ninth (m9). We chose to use these intervals because they are consistently rated as dissonant (e.g., Bidelman & Krishnan, 2009; Itoh, Miyazaki, & Nakada, 2003) and are also discriminated by non-human animals (McDermott & Hauser, 2004). For the test phase, intervals were the major seventh (M7), the minor seventh (m7) and the major second (M2). As in Experiment 1, there were 12 different stimuli for the training phase and 12 novel stimuli for the test phase. In each phase, half of the stimuli followed the AAB pattern and half the ABC sequences (see table 2).

Apparatus and procedure

The apparatus and procedure were the same as in Experiment 1.

Results and discussion

For the training phase, a repeated measures ANOVA was run with session (1-30) as the within-subject factor. The analysis showed a significant difference between sessions $F = (29, 551) = 27.3$, p < .001, $\eta_p^2 = .591$ with a progressive increase in lever pressing responses to target stimuli. For the test session, only data from test stimuli were analyzed. A one-sample t test showed that the mean percentage of responses to novel AAB sequences was significantly above what is expected by chance ($M = 58.5$, $SD = 6.03$), $t(19) = 6.27$, $p < .001$, 95% CI [55.5, 61.3], $d = 1.40$. Thus, as with consonant stimuli, rats learn to discriminate and generalize rules implemented over dissonant intervals. Comparisons between Experiments 1 and 2 yielded a very similar pattern of results. A t test comparing both experiments showed that the animals generalized their responses to the novel test stimuli $t(37) = 0.75$, $p = .459$, 95% CI [-2.70, 5.87], $d = 0.24$. Thus, the difference between consonance and dissonance in acoustic stimuli does not seem influence structure extraction of abstract patterns in rats.

Experiment 3: Mapping consonance to abstract categories

The present experiment explores whether consonance and dissonance act as perceptual anchors that might help rats to structure an acoustic signal. Even though no differences were observed in a rule learning task over consonant (Experiment 1) and dissonant intervals (Experiment 2) in non-human animals, mapping between perceptual categories and variables in an abstract pattern has been shown to facilitate structure extraction (Comins & Genter, 2013). It is thus possible that implementing the rules over different types of intervals could

facilitate the task of pattern detection to the animals. To explore this, the AAB rules were implemented over both consonant and dissonant intervals. In contrast to the previous experiments, consonant intervals were only used in the A positions of the rule, while dissonant intervals were only used in the B position of the rule.

Subjects

Subjects were twenty new female Long-Evans rats that were 5 months old.

Stimuli

Stimuli followed the same pattern as in the Experiments 1 and 2. However, for the AAB structure in the present experiment, consonant intervals (the octave, the fifth and the fourth) were always placed in the position of A, while dissonant intervals (the tritone, the minor second and the minor ninth) were always placed in the position of B (so the AAB pattern was implemented as consonant-consonant-dissonant sequences). As in previous experiments, intervals were organized at random for the non-target stimuli (ABC), including both consonant and dissonant intervals. Test intervals for the A category (consonance) were the minor third, the major third and the major sixth; while test intervals for the B category (dissonance) were the major seventh, the minor seventh and the major second (see table 3).

Apparatus and procedure

The apparatus and procedure were the same as in the previous experiments.

Results and discussion

As in Experiments 1 and 2, a repeated-measure ANOVA was run with session (1-30) as the within-subject factor for discrimination training. The analysis showed a significant difference between sessions $F = (29, 551) = 19.8$, $p < .001$, $\eta_p^2 = .509$ indicating that rats successfully discriminated target from non-target sequences as there was an increase in responses to target stimuli, reflected by the higher percentage of responses to target stimuli (see Figure 2). A one-sample t test over the test data showed that the mean percentage of responses to novel AAB sequences was significantly above what is expected by chance ($M = 61.1$, $SD = 8.17$), $t(19) = 6.07$, $p < .001$, 95% CI [57.3, 64.9], $d = 1.36$. Thus, as in the previous experiments, rats generalized the learned discrimination to novel sequences.

Independent sample t tests comparing results from the generalization tests across experiments revealed that performance in the present experiment did not differ from the performance observed with sequences that only contained consonant intervals (Experiment 1), $t(37) = -0.43$, $p = .668$, 95% CI [-6.06, 3.93], $d = 0.13$, and dissonant intervals (Experiment 2), $t(38) = -1.17$, $p = .251$, 95% CI [-7.24, 1.95], $d = 0.37$. That is, rats did not show an improvement in their performance when there was a mapping between categories in the AAB pattern and consonant and dissonant intervals. Similarly, a comparison of the mean percentage of responses to reinforced stimuli (AAB sequences) during discrimination training with experiment (1, 2 and 3) as the between-subjects factor, and session (1-30) as the within-subject factor, yielded significant differences between sessions, $F(29, 522) = 44.5$, $p < .001$, and no differences between experiments, $F(1, 18) = 0.24$, $p = .625$, nor interaction between the factors $F(29, 522) = 0.74$, $p = .829$, suggesting that rats learn rules

at the same rate over musical intervals independently of how consonant they are. This also provides evidence that the present experimental procedure can be used to explore rule learning in rats, as the animals displayed successful generalization in all the tests. Lack of differences across experiments do not seem to be related to relatively low numerical performance during the test, as the animals consistently discriminated between test items. A floor effect in performance would yield the opposite result (no discrimination between test items). However, all the experiments showed reliable generalization to novel items not presented during training. Taken together, the results from Experiment 1 to 3 provide no evidence that the rats have a processing advantage for consonance over dissonance (see Figure 4).

The results observed so far suggest that differences in consonance and dissonance do not modulate rule learning in non-human animals. However, different studies with human participants have observed a processing advantage for consonance over dissonance (Komeilipoor et al., 2015; Schellenberg & Trehub, 1994; 1996). It is thus important to explore if such differences in sensory consonance do produce an effect in a rule learning task in humans that is analogous to the task presented to the animals. In the next series of experiments we explore whether consonance might bring a processing advantage in an abstract rule learning task for human participants living in a Western culture. For this, we tested human participants with the same stimuli that we had presented to the animals.

Experiment 4: Rule learning over consonant intervals by humans

Experiment 4a

In the present experiment we explored rule extraction over consonant interval sequences in human participants. As with rats, human participants were presented with a series of sequences composed by three consonant intervals that always followed an AAB pattern. To test for generalization, we presented participants with new intervals not used during training.

Participants

Participants were 38 undergraduate students (25 women; mean age = 21 years, 2 months) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

Stimuli were the same as the ones used with rats in Experiment 1 (see table 2). Stimuli were sequences of three two-note consonant intervals that either followed an AAB (target) or ABC (non-target) pattern.

Apparatus

Participants were tested individually in a sound attenuating room. The auditory stimuli were presented through Sennheiser HD 515 headphones. Psyscope XB57 software was used to program and run the experiment.

Procedure

Similar to the previous experiments, the experiment consisted of a training phase followed by a test phase. During training, participants were presented with a go/no-go task. Participants were instructed to press a button on the keyboard after the presentation of each stimulus to find out which stimuli were "correct" and which stimuli were "incorrect". After each response, feedback was provided on the screen ("correct" if the participant pressed the button after target stimuli [AAB pattern] and "incorrect" if the participant pressed the button after non-target stimuli [ABC sequence]). Participants were also instructed they should try to press the button only after "correct" stimuli. Stimuli were presented in a balanced manner and no more than two stimuli of the same type could follow each other. There was an inter-stimulus interval of 2000 ms. Training contained at least 30 trials and lasted until participants had reached a criterion of 3 consecutive correct responses. Once this criterion was reached, the test phase began. For the test phase, we used a two-alternative forced choice task (a task that has extensively been used in the adult rule learning literature and that nicely displays participants' generalization abilities). It consisted of twelve trials. In each trial, participants were presented with two stimuli, target and non-target. Participants were asked to indicate which one was more similar to the "correct" stimuli in the training phase. Test sequences consisted of new intervals not presented during training. Nov feedback was provided during test.

Results and Discussion

For the training phase, the mean number of trials participants needed to reach the criterion of 3 consecutive correct responses was 34.8 ($SD = 7.60$). A one-sample t test over the test data showed that the percentage of correct responses was significantly above chance, $M = 73.5$, $SD = 20.5$, $t(37) = 7.05$, $p < .001$, 95% CI [66.7, 80.2], $d = 1.14$, providing evidence for rule learning over consonant intervals. Thus, participants successfully learned the discrimination during training after relatively few trials and generalized the learned rule to novel consonant interval sequences during test. To be sure that any putative differences observed in humans were not due to specific features in the stimuli used, we ran a control after each experiment varying the abstract structure to be learned and the intervals implementing it.

Experiment 4b

Results from the previous experiment show human participants successfully generalize abstract rules implemented over consonant intervals. To rule out the possibility that the positive results observed in Experiment 4a were only due to specific features of the stimuli used such as the structure of the rule, the combination of specific intervals, or the frequency range at which intervals were played, we ran Experiment 4b. In this experiment we explored whether the same level of performance is observed when consonant intervals are used to implement an ABA rule. We also changed the intervals used during training and test and shifted the scale at which intervals were played.

Participants

Participants were a new group of 30 undergraduate students (20 women; mean age = 22 years, 5 months) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

In the present experiment we used a different target abstract pattern (ABA instead of AAB), as well as different training and test interval sequences, implemented at a different octave (all intervals were played at the C_4 octave, with a fundamental frequency of 261.63 Hz, instead of the C_5 octave that has a fundamental frequency of 523.25 Hz). Target sequences followed an ABA pattern, so the first and last intervals of the sequence were the same and the second interval was different (e.g., fourth-minor third-fourth). Non-target stimuli had three different intervals in a random sequence ABC (e.g., minor third-octave-fourth). Intervals used for the training phase were the octave, the minor third and the fourth. As in Experiment 4a there were 6 target (ABA) and 6 non-target stimuli (ABC).

For the generalization test we created 12 novel stimuli (6 following an ABA pattern and 6 following a random sequence ABC). Test stimuli were made by different intervals (major third, fifth and major sixth) that were not used during training. All intervals were played in the C_4 octave. Each sequence of three intervals was 2 seconds long, with tempo of 80 beats per second.

Apparatus and Procedure

The apparatus and procedure were the same as in Experiment 4a.

Results and Discussion

The mean number of trials participants needed to reach the criterion of 3 consecutive correct responses in the training phase was 37.3 ($SD = 9.92$). As in Experiment 4a, the percentage of correct responses was significantly above chance, $M = 69.9$, $SD = 15.7$, $t(29) = 6.97$, $p < .001$, 95% CI [64.1, 75.9], $d = 1.27$, providing evidence for rule learning over consonant intervals. Independent sample t tests comparing the generalization test results from Experiments 4a and 4b revealed no significant differences between them, $t(66) = 0.77$, $p = .447$, 95% CI [-5.58, 12.5], $d = 0.20$. Therefore, participants generalized the learned rule to novel interval sequences at the same level as in Experiment 4a. Thus, the performance observed in Experiment 4a was not specific to the stimuli used during training and test (see Figure 3). In the next experiment we explored whether the same level of generalization performance could be observed when the rules are implemented over dissonant intervals.

Experiment 5: Rule learning over dissonant intervals by humans

Experiment 5a

In Experiment 5a we tested rule learning over dissonant intervals. The present experiment was identical to Experiment 4a, but only dissonant intervals were used during training and test.

Participants

Participants were a new group of 38 undergraduate students (25 women; mean age = 20 years, 7 months) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

Stimuli were the same as the ones used rats in Experiment 2 (see table 2). Stimuli were sequences of three two-note dissonant intervals that either followed an AAB (target) or ABC (non-target) pattern. As in Experiment 4a, sequences were played in the C_5 octave.

Apparatus and Procedure

The apparatus and procedure were the same as in Experiment 4.

Results and discussion

The mean number of trials participants needed to reach the criterion of 3 consecutive correct responses in the training phase was 41.9 (SD = 26). Although participants of the present experiment needed a greater number of trials than participants in Experiment 4a (M = 34.8), this difference did not reach significance, t (74) = -1.63, p = .108, 95% CI [-15.9, 1.60], d = 0.25. A one-sample t test analysis on the test data showed that the percentage of correct responses was significantly above chance, M = 64.3, SD = 16.9, t (37) = 5.17, p < .001, 95% CI [58.7, 69.8], d = 0.83. Thus, participants learned to discriminate and generalize the AAB rule over dissonant interval sequences. An independent sample t test comparing tests results from Experiment 4a and 5a revealed significant differences between them, t (74) = 2.13, p = .036, 95% CI [0.61, 17.8], d = 0.50. Thus, even though human participants can generalize an abstract pattern over dissonant intervals, they perform better in this task when the patterns to be generalized are implemented over consonant intervals.

Experiment 5b

As in Experiment 4b, it is important to be sure that the decreased performance in the generalization of abstract structures over dissonant intervals is not only due to the specific AAB sequence we used in Experiment 5a or the combination of specific intervals used during training and test. For this reason in the present experiment we implemented an ABA rule, and dissonant intervals used during training and test were combined differently.

Participants

Participants were a new group of 30 undergraduate students (22 women; mean age = 20 years, 10 months) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

The stimuli included the same changes as in Experiment 4b. Target stimuli followed an ABA (instead of an AAB) pattern, we used different combinations of intervals from those used in Experiment 5a, and all intervals were implemented in the C_4 (instead of the C_5) octave. Random sequences (ABC) composed of three different intervals were used for non-target

stimuli. As in Experiment 5a, dissonant intervals were used to create the sequences. For the training phase, we used the tritone, the minor second and the major seventh. For the test phase, intervals were the minor ninth, the minor seventh and the major second. There were 12 different stimuli for the training phase and 12 novel stimuli for the test phase. In each phase, half of the stimuli followed the ABA pattern and half were ABC sequences.

Apparatus and Procedure

The apparatus and procedure were the same as in Experiment 5a.

Results and Discussion

The mean number of trials needed to reach the criterion during training was 44.1 ($SD =$ 18.8). The percentage of correct responses during test was significantly above chance, $M =$ 60.3, $SD = 19.3$, $t(29) = 2.92$, $p = .007$, 95% CI [53.1, 67.5], $d = 0.95$, providing evidence for rule learning over dissonant intervals. Independent sample t tests comparing the generalization test results from Experiments 5a and 5b (both experiments in which the rule was implemented over dissonant intervals) revealed no significant differences between them, $t(66) = 0.90$, $p = .370$, 95% CI [-4.82, 12.8], $d = 0.22$. Thus, participants generalized the learned rule to novel dissonant intervals at same level as in Experiment 5a. Independent sample t tests comparing test results from Experiments 4b and 5b (both experiments in which the target rule was ABA) revealed significant differences between them, $t(58) = 2.14$, $p = .037$, 95% CI [0.63, 18.8], $d = 0.55$, providing further evidence for lower performance when rules are implemented over dissonant intervals than when they are implemented over consonant intervals in human participants. Thus, the fact that rules were more readily detected when they were implemented over consonant intervals (Experiment 4) is consistent with the processing advantage for consonance over dissonance described in Schellenberg and Trehub (1994; 1996). As the participants tested in our experiments lived in a Western culture, the results fits well with the idea developed by McLachlan and collaborators (2013) according to which familiarity with the chords facilitates pitch perception, leading to an increased performance when the task contains consonant intervals.

Experiment 6: Consonance as a perceptual anchor

Experiment 6a

As in experiment 3 with rats, the present experiment explores whether consonance and dissonance might act as perceptual anchors that might help human listeners to structure the acoustic signal. We implemented the AAB rules over both consonant and dissonant intervals. Consonant intervals were only used in the A positions of the rule, while dissonant intervals were only used in the B position of the rule.

Participants

Participants were a new group of 38 undergraduate students (24 women; mean age = 21 years, 9 months) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

Stimuli were the same as the ones used with rats in Experiment 3 (see table 3). Stimuli were sequences of three two-note intervals that either followed an AAB (target) or ABC (non-target) pattern. Each stimulus contained both, consonant and dissonant intervals. Consonant intervals were only used in the A positions of the rule, while dissonant intervals were only used in the B position of the rule. For the non-target stimuli the random sequences (ABC) were also composed of both, consonant and dissonant intervals, so the ABC sequences resulted in the same number of stimuli having either all three consonant, dissonant or mixed intervals (n = 2 of each). Sequences were played in the C_5 octave.

Apparatus and Procedure

The apparatus and procedure were the same as in Experiments 4 and 5.

Results and discussion

The mean number of trials participants needed to reach the criterion of 3 consecutive correct responses during the training phase was 39.7 ($SD = 25.2$). Results from the test demonstrate that participants generalized the pattern learned during training to novel stimuli, $M = 84.2$, $SD = 18.7$, $t(37) = 11.3$, $p < .001$, 95% CI [78.1, 90.3], $d = 1.83$. Performance in the present experiment was higher than performance observed with sequences that only contain consonant intervals (Experiment 4a), $t(74) = 2.38$, $p = .019$, 95% CI [1.78, 19.7], $d = 0.55$, and dissonant intervals (Experiment 5a), $t(74) = 4.87$, $p < .001$, 95% CI [11.8, 28.1], $d = 1.12$. Thus, mapping between categories in the AAB pattern and consonant and dissonant intervals helps listeners to structure the signal to the point of facilitating rule learning.

Experiment 6b

In Experiment 6a, mapping consonance to abstract categories improved rule generalization. However, two concerns might be raised regarding these results. First, in the previous experiment, target stimuli contained a repetition in the abstract structure (AAB), while there were no repetitions in the ABC stimuli (all intervals were different in each sequence). To avoid any possible confounds of comparing a repeating versus a non-repeating pattern, in the present experiment both target and non-target stimuli include the reduplication of an interval. Thus, in Experiment 6b target stimuli follow an AAB pattern while non-target stimuli follow and ABB pattern. Second, in Experiment 6a all target stimuli began with a consonant interval, while only half of the non-target stimuli began with a consonant interval (because intervals composing non-target stimuli were randomized). This pattern could have led participants to focus only on the first interval during test. To control for this, in the present experiment all the stimuli, targets and non-targets, began with a dissonant interval.

Participants

Participants were a new group of 38 undergraduate students (28 women; mean age 21 years, 1 month) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

Target stimuli followed the same AAB pattern as in the previous experiments, while non-target stimuli followed an ABB pattern, including also a repetition of an interval. As in Experiment 6a, consonant and dissonant intervals were included in each sequence. However, in the present experiment, items belonging to the A category were dissonant and items for the B category were consonant. Thus, target stimuli resulted in dissonant-dissonant-consonant sequences and non-target stimuli resulted in dissonant-consonant-consonant sequences. For the training phase the dissonant intervals assigned to the A category were the tritone, the minor second and the major seventh, and the consonant intervals assigned to the B category were the octave, the minor third and the fourth. Test intervals for the A category (dissonance) were the minor ninth, the minor seventh and the major second. Intervals for the B category (consonance) were the major third, the fifth and the major sixth.

Apparatus and Procedure

The apparatus and procedure were the same as in the previous experiments.

Results and discussion

The mean number of trials participants needed to reach the training criterion was 40.5 ($SD =$ 26.7). Results from the test demonstrate that participants generalized the pattern learned during training to novel stimuli, $M = 82.9$, $SD = 16.4$, $t(37) = 12.3$, $p < .001$, 95% CI [77.5, 88.3], $d = 2$. Independent sample t tests comparing results from the generalization tests of Experiments 6a and 6b revealed no significant differences between them, $t(74) = 0.33$, $p = .745$, 95% CI [-6.72, 9.35], $d = 0.07$. Performance in the present experiment was higher than performance observed with sequences that only contain consonant intervals (Experiment 4a), $t(74) = -2.21$, $p = .030$, 95% CI [-17.9, -0.94], $d = 0.51$, and dissonant intervals (Experiment 5a), $t(74) = -4.86$, $p < .001$, 95% CI [-26.3, -11.0], $d = 1.12$. These results, together with results from Experiment 6a, support the idea that musical consonance acts as categorical anchor that helps listeners to detect structures in the signal. The more different stimuli corresponding to A and B categories were perceived by the participants during training, the easier it was for them to pick up the abstract pattern. Thus, when consonant and dissonant intervals are mapped to A and B categories forming an abstract pattern, participants' performance in a rule learning task reliably improves when compared with their performance over consonant or dissonant sequences.

An alternative explanation to the enhancement observed in experiments 6a and 6b is that it is only due to the greater variability in the intervals composing the sequences compared to those used in Experiments 4 and 5. That is, sequences in Experiment 6 contained a more diverse set of intervals coming from consonant and dissonant categories, while sequences in Experiment 4 and 5 contained intervals coming only from either the consonant or the dissonant category. To test whether only increased variability (and not the mapping between consonance and abstract categories) is responsible for improved performance, in Experiment 7 we created sequences made by both consonant and dissonant intervals, but we scrambled interval types across A and B categories composing the AAB structure.

Experiment 7: Is variability responsible for higher performance?

In Experiment 7 we explored the possibility that improved performance observed in Experiment 6 is just a result of increased stimuli variability with respect to Experiments 4 and 5. As in Experiments 6, sequences were composed by both consonant and dissonant intervals, but there was no matching between intervals and categories in the structure (both the A and B categories were composed of consonant and dissonant intervals).

Participants

Participants were a new group of 38 undergraduate students (27 women; mean age = 21 years, 9 months) from the Universitat Pompeu Fabra with no formal musical training. They received monetary compensation for their participation in the study.

Stimuli

In the present experiment we used the same consonant and dissonant intervals to create the sequences as in Experiment 6a. In contrast to the previous experiment, the A and B categories in the AAB sequences included both consonant and dissonant intervals. For the training phase, intervals assigned to the A category were the octave, the tritone and minor second. Intervals assigned to the B category were the fifth, the fourth and minor ninth. This resulted in sequences such as octave-octave-minor ninth, minor second-minor second-fourth, or tritone-tritone-minor ninth (see table 3). For the test phase, the A category included the minor third, the major seventh and the minor seventh. The B category included the major sixth, the major second and the major third. As in Experiment 6a, intervals used to create the non-target stimuli were organized at random.

Apparatus and Procedure

The apparatus and procedure were the same as in the previous experiments.

Results and discussion

The mean number of trials participants needed to reach the criterion of 3 consecutive correct responses during the training phase was 41.9 ($SD = 28.7$). During test, participants correctly generalized the pattern learned during training to novel stimuli, $M = 73.9$, $SD = 21.6$, $t(37) = 6.82$, $p < .001$, 95% CI [66.8, 81.0], $d = 1.10$. Interestingly, there were significant differences between the results of the present experiment and those from Experiment 6a, $t(74) = -2.23$, $p = .029$, 95% CI [-19.5, -1.08], $d = 0.51$, and 6b, $t(74) = -2.04$, $p = .044$, 95% CI [-17.8, -0.22], $d = 0.47$ suggesting that the presence of both consonant and dissonant intervals by itself was not driving improved performance. In fact, results from the current experiment were not significantly different from those observed when the rule was implemented over consonant intervals in Experiment 4a, $t(74) = -0.09$, $p = .928$, 95% CI [-9.18, 10.1], $d = 0.02$, and 4b $t(66) = 0.83$, $p = .409$, 95% CI [-5.47, 13.3], $d = 0.21$. Thus, when there was no mapping between categories forming the pattern to be learned and consonance, no improvement was observed with respect to rule learning over consonant intervals. However, results from Experiment 7 differed from those of Experiment 5a, $t(74) = 2.16$, $p = .034$, 95% CI [0.77, 18.5], $d = 0.55$, and 5b $t(66) = 2.71$, $p = .009$, 95% CI [3.58,

23.7], $d = 0.67$, underlining the processing cost that learning patterns over only dissonant intervals might have.

From experiments 4 to 7 we tested whether consonance modulates the detection of abstract patterns in human participants. We included several experimental controls to be sure the observed pattern of results was reliable and was not only a consequence of specific intervals or structures used. Taken together, results observed in human participants suggest that consonance facilitates the detection of abstract patterns.

General Discussion

In the present study we explored the role of consonance and dissonance in the extraction and generalization of token-independent rules from a comparative perspective. Results show that both human and non-human animals can learn and generalize rules implemented over different sets of musical intervals. However, there seem to be differences across species regarding the extent to which they benefit from differences in sensory consonance.

Results show that rats learned to discriminate rules over sets of musical intervals and generalized their discrimination to novel intervals not presented during training. However, there was no evidence that consonance had any effect on rule learning, as no differences were observed across experiments. The ability of rats to detect rules over sequences of musical intervals was not modulated by the intervals implementing the rule. Performance in the rule-learning task did not change when the sequences contained consonant intervals (Experiment 1), dissonant intervals (Experiment 2) or both consonant and dissonant intervals in the same sequence (Experiment 3). Results from human participants provide a contrasting picture. For humans, rules are more readily detected when they are implemented over consonant intervals (Experiment 4) than over dissonant intervals (Experiment 5). Beyond that, mapping between abstract categories (consonance and dissonance) in the stimuli (A and B), and consonant and dissonant intervals noticeably helps listeners to detect structure, improving their performance in a generalization test (Experiment 6). Control experiments with human participants demonstrated that the processing advantage observed for consonant intervals was not due to the specific abstract patterns tested, or restricted to a limited set of intervals. The results from these experiments provide consistent evidence that for humans, consonance and dissonance in musical intervals can be used as perceptual anchors. Consonance helps to organize the acoustic signal as to improve the extraction and generalization of abstract rules. Non-human animals, however, do not seem to benefit from differences across musical intervals. They detect patterns with the same ease over both consonant and dissonant sequences.

Processing advantages for consonance

The present findings extend previous evidence of enhanced processing for consonance in humans. It has been shown that infants are able to detect subtle pitch changes of simultaneous and sequential tones only when the tones are related by simple frequency ratios; that is, in a context of consonance (Schellenberg & Trehub, 1996). Similarly, adults exhibit a greater difficulty detecting changes in dissonant patterns than changes in consonant

patterns (Schellenberg & Trehub, 1994). Consonance has also been shown to facilitate the synchronization of perception and action in a tapping task (Komeilipoor et al. 2015). In parallel to this evidence, in the present study we observed that consonance also facilitates the detection of abstract rules.

Results demonstrating consonance advantages in a variety of tasks add to the evidence that certain aspects of music, including rhythmic or temporal structure, facilitate cognitive processing. Conventional (Trehub & Hannon, 2009) and regular rhythms (Drake & Botte, 1993) are associated with preference and processing advantages relative to unconventional or irregular rhythms. In the case of consonance, it is an open issue whether the observed processing advantage is a result of small ratios defining consonant intervals, or a consequence of familiarity resulting from extensive experience with such intervals (e.g. McLachlan et al., 2013; Plantinga & Trehub, 2013). However, the data reported so far, together with our results, suggest that aesthetic preferences for musical consonance and rhythmic regularity seem to have parallels with regards to ease of cognitive processing.

In Experiments 6a and 6b in the present study, categories within the stimuli were mapped to consonant and dissonant intervals which resulted in increased performance during the generalization test in humans. These results are in line with previous studies suggesting that auditory perceptual categories in songbirds (Comins & Genter, 2013) and highly familiar stimuli in human infants (Marcus et al. 2007; Saffran et al. 2007) facilitate pattern learning. Thus, the processing advantage we observed when consonant and dissonant intervals align with the categories defining the structure of the stimuli (A and B) provides supportive evidence to the idea that consonance might act as a perceptual anchor for humans' auditory perception. As mentioned above, such role could arise from the listeners' prolonged experience with harmonic music. If so, the facilitation observed for consonant intervals would fit well with studies on rule learning with infants showing that highly familiar stimuli, such as pictures of domestic animals (Saffran et al. 2007), or speech (Marcus et al. 2007) facilitate the detection of abstract patterns. Studies exploring whether a similar facilitation effect is found for dissonant intervals in populations whose music systems make a more extensive use of them would help to further understand the role of experience for processing advantages observed here.

Comparing across species

Comparative work might provide key evidence regarding which components of the music faculty arise only in humans, and which might be shared across species (see for example, Hauser & McDermott, 2003; Honing, ten Cate, Peretz & Trehub, 2015). Studies with non-human animals might also help to disentangle the relative contribution that experience and the physical features of the sound might have during consonance perception. The results we observed with rats, showing that consonance and dissonance have no modulatory effect in their performance in a rule-learning task, points towards differences across species in the processing of acoustic intervals. The origin of such differences is debated. One possibility is that species such as the rat do not benefit from differences between consonance and dissonance because of their lack of extensive experience in the production and processing of harmonic sounds. Recent studies have highlighted that that experience might play a key role

during consonance processing in human adults and infants (e.g. McLachlan et al. 2013; Plantinga & Threhub; 2013). Animals in the present study might thus lack the necessary experience to display processing differences between consonance and dissonance. Thus, for the animals used in the present study, the consonant chords we presented to them differed from dissonant chords in the relative size of the interval ratios defining them, but did not differ in their familiarity.

As emphasized by Hoeschele and collaborators (2015), much more experimental work is needed to advance the understanding of the biological bases of our music abilities. Regarding the present study, it would be interesting to run further comparative studies to disentangle the relative role that experience and the physical features of the intervals might be playing in the pattern of results observed. Experiments with species that produce harmonic vocalizations could show whether such experience is enough to observe processing advantages for consonance over dissonance. One could also design an experiment in which rats are given experience with either harmonic music, or with a set of musical intervals, and test whether this would lead to a different pattern of results from the ones observed here. New studies exploring better processing of consonant intervals in human populations exposed to non-Western harmonic music could also tap into this issue. Together these experiments could certainly help to identify components of the music faculty that do not depend on specific experience. Additionally, comparative studies could provide information regarding music abilities that might be shared across species, allowing insights regarding how they might have evolved (e.g. Hauser & McDermott, 2003; Honing et al., 2015).

Conclusion

A growing body of literature shows that some aspects of musical experience might influence other cognitive domains. Studies suggest that musical rhythm, tempo and pitch processing affect performance in both linguistic and non-linguistic tasks. There is also evidence that acoustic similarity between musical tones helps in the discovery of non-adjacent statistical dependencies (Creel, Newport & Aslin, 2004). Together, these results point in the direction of complex interactions between domain-specific musical representations and general structure-extraction mechanisms. In the present study we provide evidence that consonance facilitates rule learning in humans. This is likely because consonance and dissonance in musical intervals can be used as perceptual anchors that help to organize the acoustic input, making it easier for listeners to detect token-independent patterns. Lacking such role as perceptual anchors in non-human animals, consonance and dissonance do not seem to modulate rule learning.

Acknowledgements

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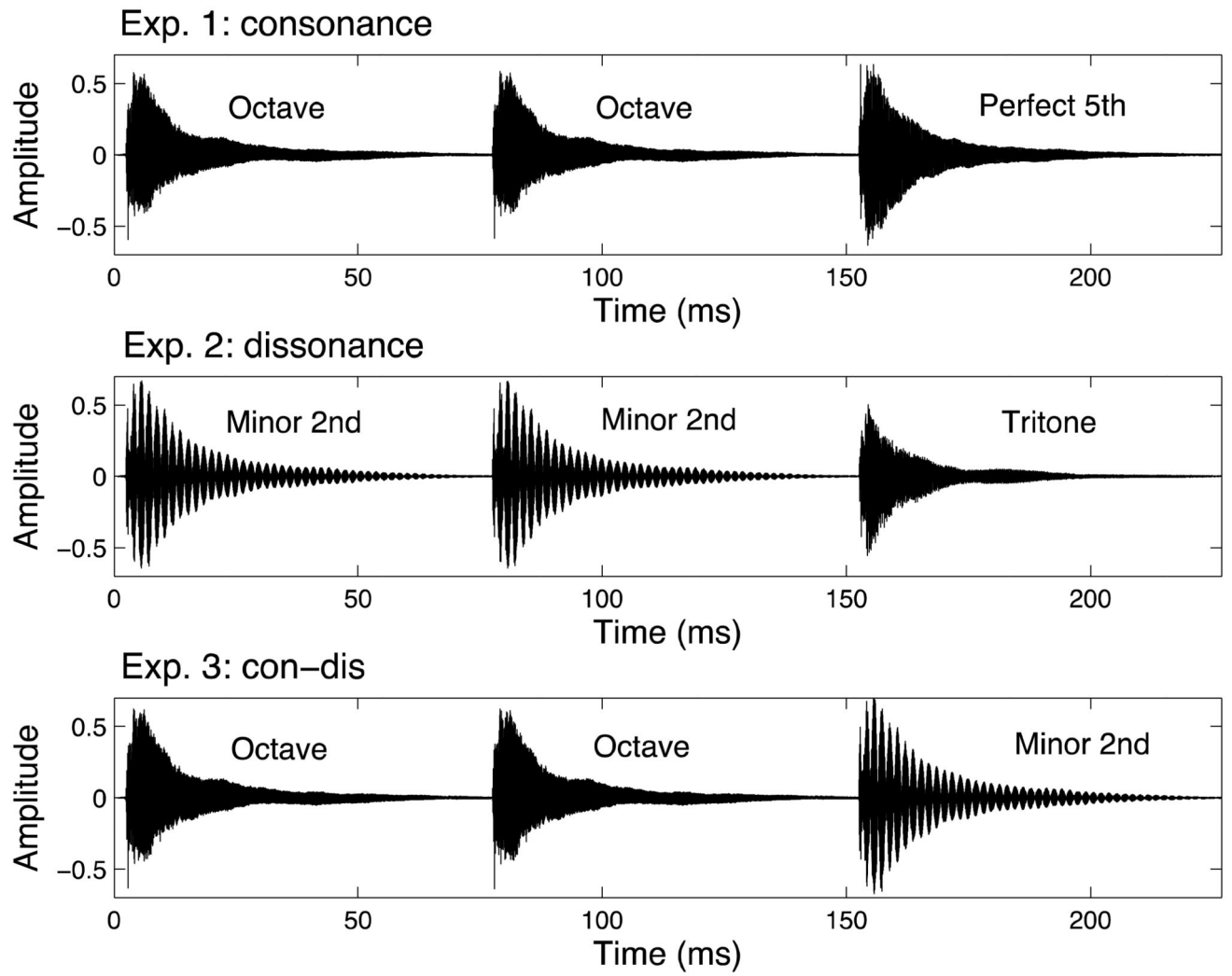
Figure 1.
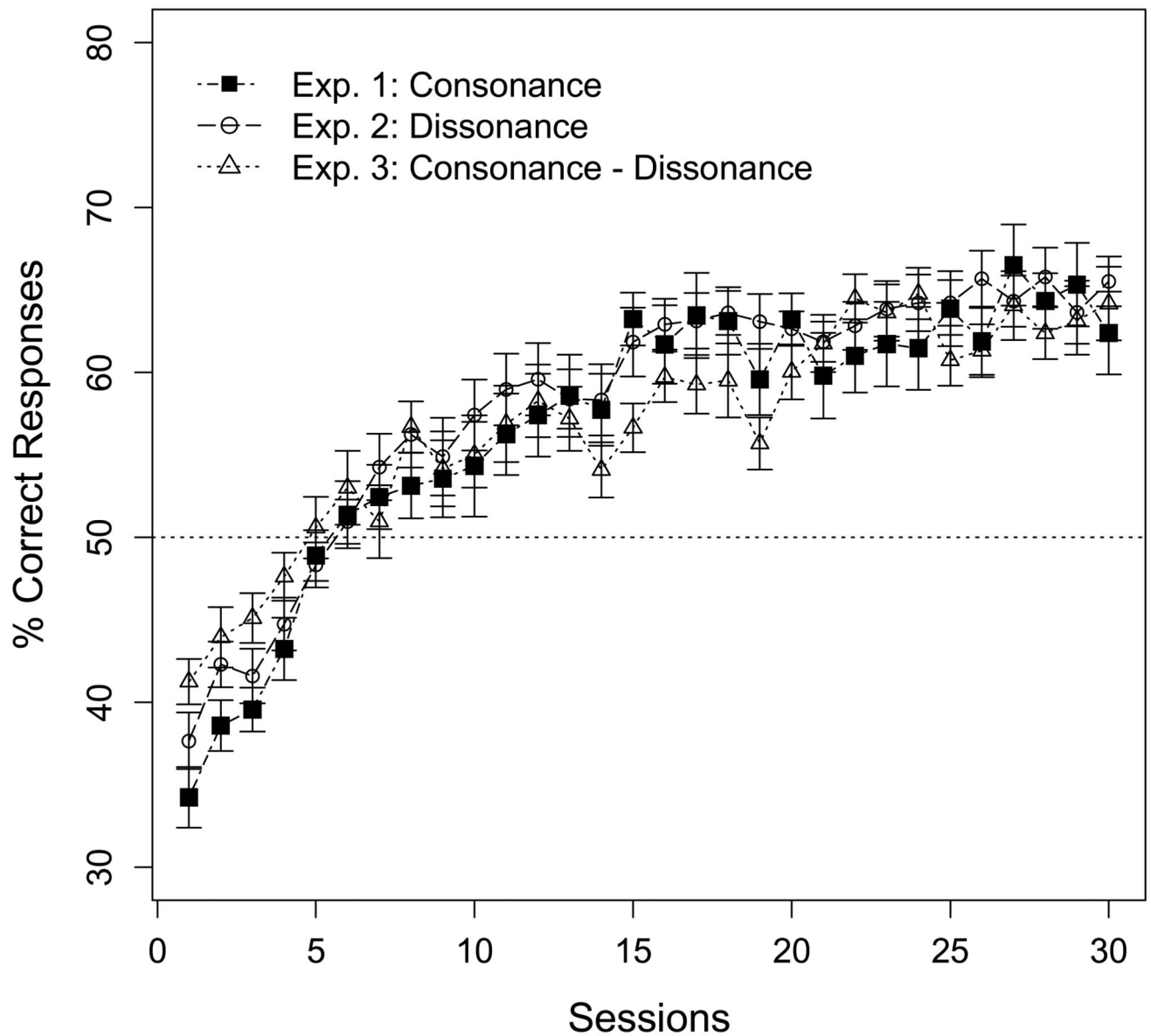Waveforms for target stimuli (AAB) used in the experiments.

Figure 2.
Mean percentage (and standard error bars) of rats' responses during 30 training sessions to target stimuli in Experiment 1 (consonance; black squares), Experiment 2 (dissonance; white circles) and Experiment 3 (consonance-dissonance; white triangles). A performance of 50% suggests no discrimination between stimuli. Rats successfully learned to discriminate rules implemented over consonant and dissonant intervals.
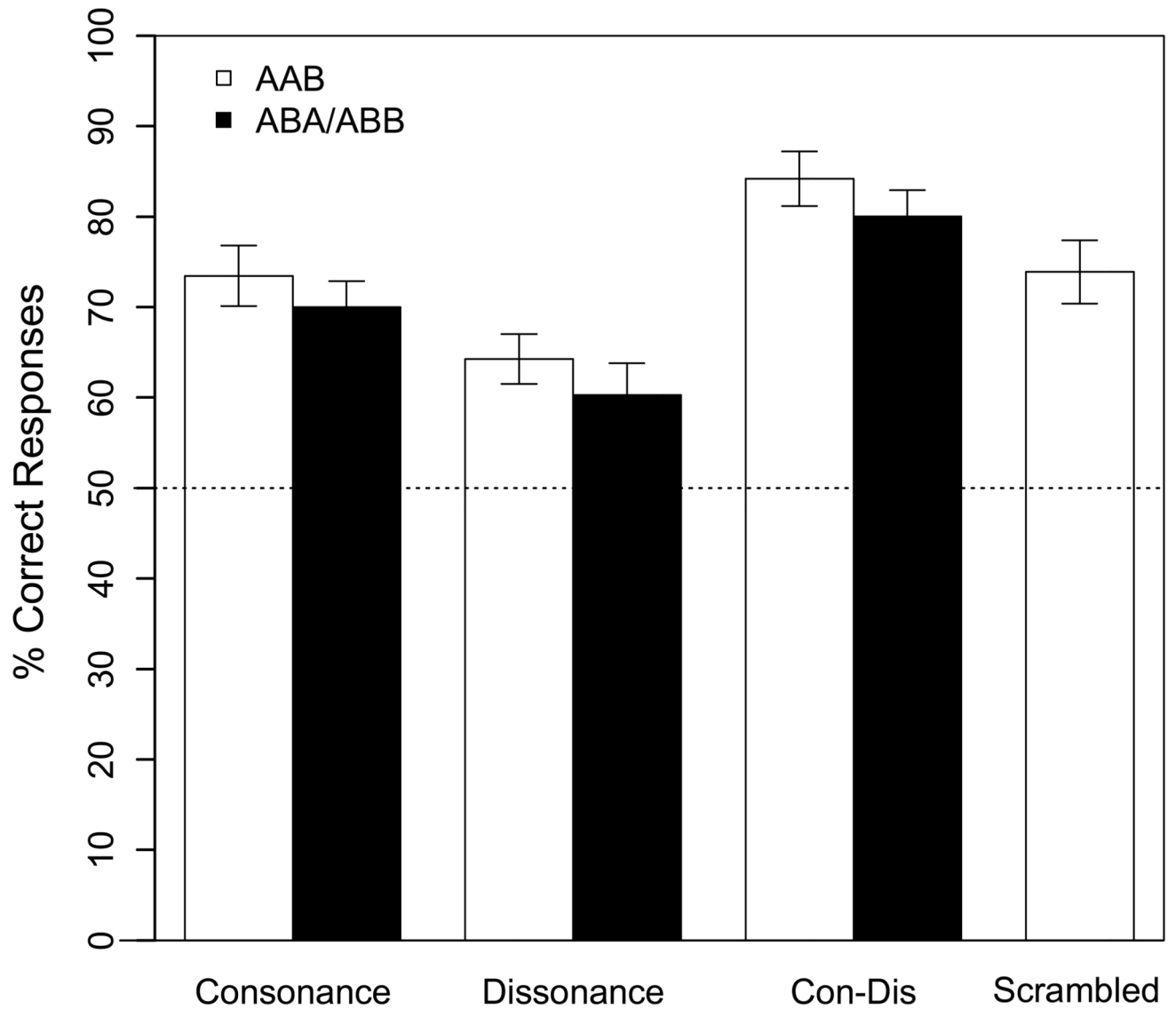
Figure 3.
Mean percentages (and standard error bars) of human participants' correct responses during
test. The performance was significantly above chance in all conditions. However,
generalization was better over consonant than over dissonant intervals. Performance also
improved when the consonant and dissonant intervals were mapped to the abstract categories
defining the rule. The improved performance was not due to greater variability in the stimuli.

Rats

Humans

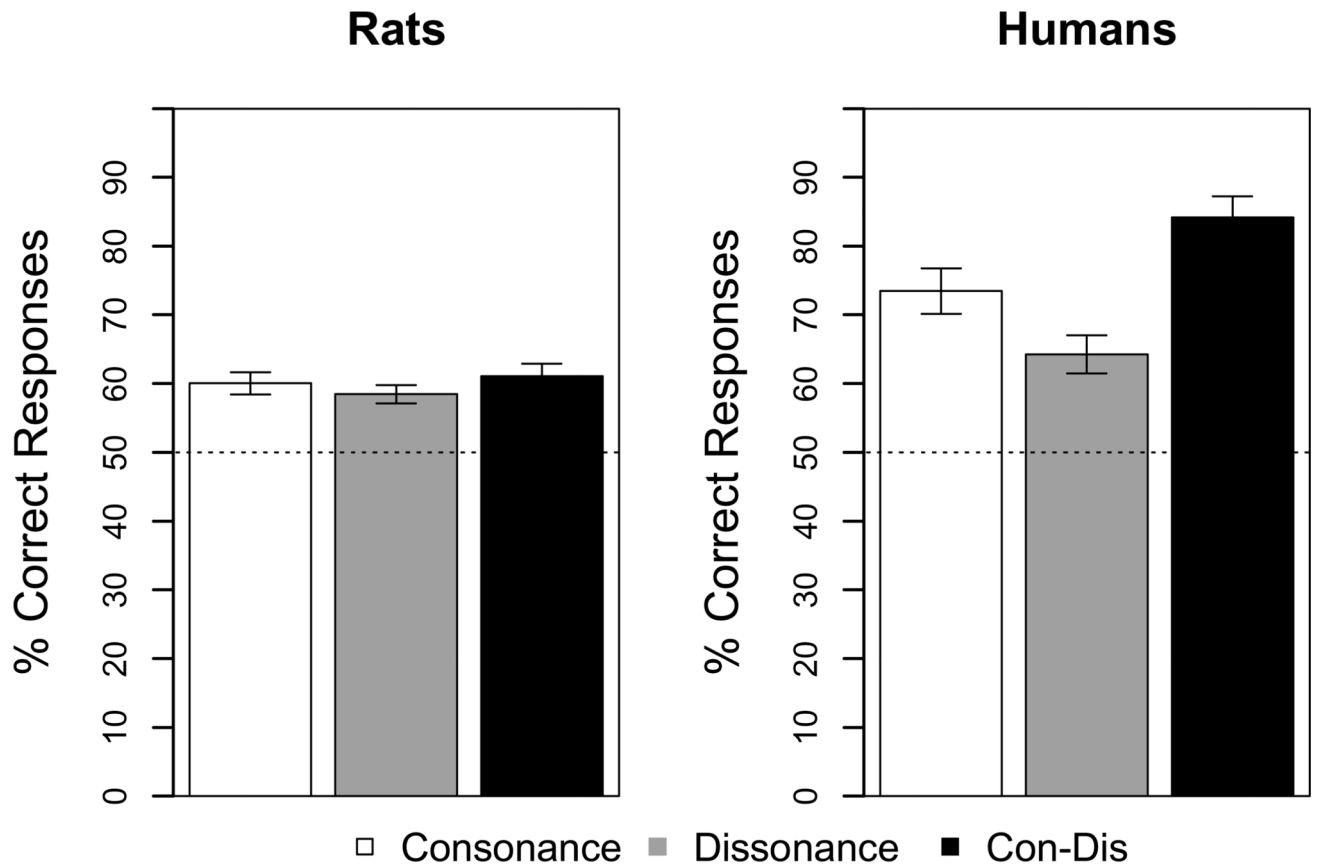□ Consonance ■ Dissonance ■ Con-Dis

Figure 4.
Mean percentages (and standard error bars) of correct responses during test for both animals and humans (collapsed data across experiments). The performance was significantly above chance in all conditions. Animals' performance was not modulated by the intervals at which the rule was implemented. In contrast, such modulation was observed in human participants.

Table 1

Intervals Used During Training and Test in Experiments 1, 2, 3, 4a, 5a, 6a and 7

	Consonant			Dissonant		
	Intervals		Ratio	Intervals		Ratio
Training	Octave	(P8)	2:1	Tritone	(TT)	45:32
	Fifth	(P5)	3:2	Minor 2nd	(m2)	16:15
	Fourth	(P4)	4:3	Minor 9th	(m9)	15:32
Test	Minor 3rd	(m3)	6:5	Minor 7th	(m7)	16:9
	Major 3rd	(M3)	5:4	Major 7th	(M7)	15:8
	Major 6th	(M6)	5:3	Major 2nd	(M2)	9:8

Note. Intervals (with short name in parenthesis) and frequency ratios used in Experiments 1, 2, 3, 4a, 5a, 6a and 7. Rats and human participants were trained to discriminate interval sequences following an AAB pattern from random interval sequences. During test, subjects were presented with sequences composed by novel intervals not presented during training.

Table 2

Interval Sequences Used During Training and Test in Experiments 1, 2, 4a and 5a

	Experiments 1 and 4a		Experiments 2 and 5a	
	AAB	*Random*	*AAB*	*Random*
Training	P8-P8-P5	P8-P5-P4	TT-TT-m2	TT-m2-m9
	P8-P8-P4	P8-P4-P5	TT-TT-m9	TT-m9-m2
	P5-P5-P8	P5-P8-P4	m2-m2-TT	m2-TT-m9
	P5-P5-P4	P5-P4-P8	m2-m2-m9	m2-m9-TT
	P4-P4-P8	P4-P8-P5	m9-m9-TT	m9-TT-m2
	P4-P4-P5	P4-P5-P8	m9-m9-m2	m9-m2-TT
Test	m3-m3-M3	m3-M3-M6	M7-M7-m7	M7-m2-M2
	m3-m3-M6	m3-M6-M3	M7-M7-M2	M7-M2-m7
	M3-M3-m3	M3-m3-M6	m7-m7-M7	m7-M7-M2
	M3-M3-M6	M3-M6-m3	m7-m7-M2	m7-M2-M7
	M6-M6-m3	M6-m3-M3	M2-M2-M7	M2-M7-m7
	M6-M6-M3	M6-M3-m3	M2-M2-m7	M2-m7-M7

Note. Interval sequences used in Experiments 1 & 4a (consonance) and Experiments 2 & 5a (dissonance). Each experiment included target sequences (AAB) and non-target sequences (random) for the training phase as well as for the test phase.

Table 3

Interval Sequences Used During Training and Test in Experiments 3, 6a and 7

	Experiment 3 and 6a		Experiment 7	
	AAB	*Random*	*AAB*	*Random*
Training	P8-P8-TT	P8-P5-P4	P8-P8-P5	P8-P5-P4
	P8-P8-m2	P4-P5-P8	P8-P8-m9	P4-P5-P8
	P5-P5-TT	TT-m2-m9	TT-TT-P4	TT-m2-m9
	P5-P5-m9	m9-m2-TT	TT-TT-m9	m9-m2-TT
	P4-P4-m2	P5-m2-P8	m2-m2-P5	P5-m2-P8
	P4-P4-m9	m2-P4-TT	m2-m2-m9	m2-P4-TT
Test	m3-m3-M7	M3-m3-M6	m3-m3-M6	M3-m3-M6
	m3-m3-m7	M3-m7-m3	m3-m3-M2	M3-m7-m3
	M3-M3-M7	M6-m3-M3	M7-M7-M6	M6-m3-M3
	M3-M3-M2	M7-M2-m7	M7-M7-M2	M7-M2-m7
	M6-M6-m7	m7-M2-M7	m7-m7-m3	m7-M2-M7
	M6-M6-M2	M2-M6-M7	m7-m7-M2	M2-M6-M7

Note. Interval sequences used in Experiments 3, 6a and 7. Each experiment included target sequences (AAB) and non-target sequences (random) for the training phase as well as for the test phase. Non-target sequences were the same for both experiments.