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Auditory expectations for newly acquired structures

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Our study investigated whether newly acquired auditory structure knowledge allows listeners to develop perceptual expectations for future events. For that aim, we introduced a new experimental approach that combines implicit learning and priming paradigms. Participants were first exposed to structured tone sequences without being told about the underlying artificial grammar. They then made speeded judgements on a perceptual feature of target tones in new sequences (i.e., in-tune/out-of-tune judgements). The target tones respected or violated the structure of the artificial grammar and were thus supposed to be expected or unexpected. In this priming task, grammatical tones were processed faster and more accurately than ungrammatical ones. This processing advantage was observed for an experimental group performing a memory task during the exposure phase, but was not observed for a control group, which was lacking the exposure phase (Experiment 1). It persisted when participants realized an in-tune/out-of-tune detection task during exposure (Experiment 2). This finding suggests that the acquisition of new structure knowledge not only influences grammaticality judgements on entire sequences (as previously shown in implicit learning research), but allows developing perceptual expectations that influence single event processing. It further promotes the priming paradigm as an implicit access to acquired artificial structure knowledge.

Keywords: Implicit learning; Artificial grammar; Priming; Auditory expectations; Tone sequences.

Based on knowledge about structural regularities in the natural environment (e.g., language, faces, music), perceivers develop expectations for future events, leading to facilitated processing of expected events. The priming paradigm, an indirect investigation method of perceptual expectations, has shown facilitation for structurally expected events for various materials (see McNamara, 2005, and Tillmann, 2005, for reviews in language and music, respectively). The processing of a target word is faster and more accurate when it is preceded by a semantically related word than when it is preceded by an unrelated word (e.g., Meyer & Schvaneveldt, 1971; Stanovich & West, 1979). Similarly, the processing of a target chord or tone is faster and more accurate when preceded by tonally related chords/

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tones than when preceded by unrelated ones (e.g., Bharucha & Stoeckig, 1986; Bigand, Madurell, Tillmann, & Pineau, 1999; Marmel, Tillmann, & Dowling, 2008). Priming effects reveal perceivers' knowledge about structural systems, which allows the development of perceptual expectations for future events. Language and music are two examples of structural systems encountered in everyday life. Knowledge about these systems, acquired thanks to the cognitive capacity of implicit learning, renders efficient our perception of highly probable (i.e., expected) events. Our present study investigated whether new knowledge about an artificial tone system acquired after short exposure in the laboratory allows for the development of auditory expectations, which influence accuracy and speed of tone processing.

Implicit learning research has shown that one becomes sensitive to structural regularities in artificial materials, such as artificial grammars (e.g., A. S. Reber, 1967; see Pothos, 2007, for a review). In a typical experimental paradigm, participants are first exposed to stimuli (mostly sequences of letters) that are based on a finite-state grammar, without being told about the grammatical structure. After exposure, participants are informed about the rule-governed nature of the stimuli and are required to classify novel sequences as grammatical or ungrammatical. They perform generally at above chance level, with no (or only little) verbalizable knowledge of the regularities underlying the letter sequences. For example, in A. S. Reber and Lewis (1977) participants correctly identified the grammatical status of test items for 81% of the trials, while being unable to explain their judgements.

Grammaticality judgements require participants to take into consideration the entire sequence (or letter string), and they do not inform us whether the newly acquired structure knowledge allows for the development of perceptual expectations for future events. Processing advantages for grammatical sequences have been reported with a perceptual clarification procedure for visual sequences with all letters being presented simultaneously (Buchner, 1994). A letter string was first covered by a black square, then parts of the square were continuously removed, and participants indicated as fast as possible when they identified the particular string. The observed identification times were shorter for grammatical letter strings than for ungrammatical strings (see also Kinder, Shanks, Cook, & Tunney, 2003). As the grammatical test strings had not been seen in the exposure phase, these findings show an effect of the acquired artificial grammar knowledge on the perception of new grammatical items. They thus extend facilitated processing that had been reported for repeatedly presented grammatical sequences and that had been based on memory of the same exemplars (e.g., Shanks, Wilkinson, & Channer, 2003).

For sequentially presented structures, beneficial effects of sequence learning on response times have been shown with the serial response time (SRT) paradigm: Increased exposition to structured material leads to decreased response times to events presented sequentially, thus suggesting perceivers' expectations for future events (e.g., Niessen & Bullemer, 1987). Participants make a simple response to each stimulus of a set sequence presented repeatedly (e.g., a sequence of 10 elements), usually by pressing a key to the corresponding stimulus light in a given location. Over the experimental blocks, response times to events respecting the sequence become faster, and they slow down when a new sequence is introduced. Learning is thus measured by the decrease of response times in a condition in which the stimuli appear in the structured pattern, in comparison to a condition in which the stimuli appear in random order.

However, SRT research does not allow concluding for perceptual learning and perceptual expectations based on new structure knowledge. This is due to the use of fixed sequences, the motor components involved in the task, and the use of random sequences at test. Most SRT studies showed decreased response times for a fixed sequence pattern that was repeatedly presented. And even if some studies used artificial grammars or probabilistic sequences (Cleeremans & McClelland, 1991; Schvaneveldt & Gomez, 1998; Shanks et al., 2003), the observed learning not only was perceptual, but included a motor component due to the manually given key presses. Deroost and Soetens (2006) showed that perceptual learning occurs only for "very simple deterministic sequence structure" (i.e., an eight-element sequence with first-order restrictions that cycled repeatedly), and the motor component of the responses was necessary for the acquisition of more complex sequences (see also Remillard, 2003). In addition, Reed and Johnson (1994) demonstrated that the use of random sequences at test is not adequate to study sequence learning: In comparison to the structured sequence, random sequences introduce other irregularities, such as repeated locations or new bigrams (two-element units). Controlled test sequences, which equalize first-order regularities, have been used in studies investigating sequence learning that included motor components (e.g., SOC1 vs. SOC2, Destrebecqz & Cleeremans, 2001). It is important to point out that studies testing for perceptual learning in SRT tasks have used random sequences at test (e.g., Dennis, Howard, & Howard, 2006; Deroost & Soetens, 2006).

Up to now, we thus do not know whether artificial structure knowledge acquired thanks to perceptual learning only (without concurrent motor learning) allows for perceptual expectancy formation about upcoming events in new, not previously seen sequences that obey the same artificial system (thus on a more abstract level than a repeated sequence). Previous work has shown that perceptual structure learning is not restricted to visual material (e.g., A. S. Reber, 1967), but extends to auditory material (i.e., sequentially presented event sequences), whether verbal material (e.g., spoken syllables; Saffran, Aslin, & Newport, 1996; see Saffran, 2003, for a review) or musical material based on tones (e.g., Altmann, Dienes, & Goode, 1995; McMullen & Saffran, 2004; Saffran, Johnson, Aslin, & Newport, 1999), timbres (Tillmann & McAdams, 2004), or sung syllables (Schön et al., 2008). However, none of this research has shown that the newly acquired structure knowledge allows listeners to develop perceptual expectations for future events and thus leads to more efficient processing of expected events. In studies using artificial languages, for example, perceivers learn statistical regularities for the sequentially presented syllable sequences, but the test phase requires participants to judge entire words or part-words, and thus they do not investigate perceptual expectancy formation or the influence of acquired structure knowledge on speed of event processing.

The goal of our study was to investigate whether accuracy and response time benefits can be observed for event processing without motor learning and for new sequences following the same artificial system as that for the exposure sequences (i.e., here based on a finite-state grammar). Thus, this goes beyond the investigation of a processing advantage thanks to the repeated processing of the same sequence. Put differently, does listening to artificial grammar sequences lead to knowledge that allows listeners to develop perceptual expectations for future events in new sequences?

For this goal, the exposure phase did not include a motor task, and the test phase used controlled ungrammatical items (i.e., instead of random sequences). To test for perceptual expectations, we used the priming paradigm, an implicit investigation method of listeners' knowledge and, notably, of knowledge-driven, perceptual expectations and their influence on event processing. The priming task requests participants to process rapidly and accurately a target event (e.g., word/nonword or in-tune/out-of-tune decisions in language or music studies, respectively), without judging structural relations or grammatical features. This implicit method thus allowed us to avoid informing participants about the grammar in the test phase. There has been considerable debate about what participants learn during exposure and how implicit or explicit this knowledge is (e.g., Dienes, Broadbent, & Berry, 1991; Perruchet & Pacteau, 1990). The often-used grammaticality judgements are direct, explicit measures of knowledge that require telling participants about the grammar.[1] This information

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[1] Similarly, in studies using artificial languages (whether verbal or musical), the task (i.e., judging words and part-words) also requires informing participants about the structural system (language, or language-like system).

might encourage participants in actively searching for regularities in the material (Helman & Berry, 2003). To study implicit artificial grammar knowledge, Vinter and Perruchet (1999) have argued that experimental tasks should not reveal links to the grammatical structure, but should focus on another aspect of the material. Even neurophysiological studies, which could take advantage of the indirect measures and thus avoid telling participants about the grammar, investigated neural correlates of implicit learning while asking participants to make grammaticality judgements (e.g., Petersson & Forkstam, 2004, using functional magnetic resonance imaging; Carrion & Bly, 2007, using electroencephalography, EEG). One exception is the recent EEG study by Loui, Wu, Wessel, and Knight (2009): Participants had to detect chords with a fade-out feature (i.e., decreased intensity, 10% of the trials) when listening to probable (standard) and improbable (deviant) sequences of a new musical system (based on the Bohlen–Pierce scale). For the deviant sequences, an early anterior negativity was observed. However, deviant sequences represented only 20% of the trials (vs. 70% for the standard sequences of the new musical system), and they contained a new pitch pattern that was not part of the system. The observed brain potential thus reflected also the effect of differences between high- and low-probable sequence presentations and not solely the effect of perceptual expectations based on the newly learned musical system.

In our study, an artificial grammar was based on a set of tones (forming tone sequences), instead of a set of letters (forming letter strings) as it has been done in most implicit learning research. In a first experimental phase, participants were exposed to structured tone sequences (based on the finite-state grammar displayed in Figure 1) and did a memory task (i.e., indicated after each sequence whether it had been heard previously, Experiment 1) or a detection task of mistuned tones (Experiment 2). This exposure phase contained 37 grammatical sequences, which were presented either three times (Experiment 1) or twice (Experiment 2) in random order. In the second phase, participants made speeded judgements on a perceptual feature of target tones in new sequences. The priming task was adapted from musical priming research (Bharucha & Stoeckig, 1986; Marmel et al., 2008) and required participants to judge whether a target tone was played either in tune or out of tune.[2] It allowed us to test for structure knowledge without telling participants about the grammar: The target tone either respected the artificial grammar structure or violated it by creating subtle ungrammaticalities (i.e., replacing one tone of the sequence, but without, for example, introducing new tone pairs, see Method section)—the target was thus supposed to be grammatically expected or unexpected. For this tone system, we have previously shown with the classically used grammaticality judgements (i.e., judging the entire sequences) that listeners became sensitive to the regularities underlying the used artificial grammar: Their grammaticality judgements for the new test sequences were above chance level (i.e., 58%; Poulin-Charronnat, Tillmann, Perruchet, & Molin, 2009). If the implicit artificial grammar knowledge acquired during the exposure phase allows listeners to develop auditory expectations, target tone processing should be faster and more accurate for grammatical tones than for ungrammatical tones. This processing advantage should not be observed for a control group that is lacking the exposure phase to the grammatical sequences. To investigate the knowledge acquired during the exposure phase and its influence on processing

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[2] This musical priming task has been created in parallel to the lexical decision task used in semantic priming research: Targets are either words or nonwords, and data analyses focus on the processing of the target words. For the purpose of the priming task used in our present study, test sequences were presented with the target tone being played either in tune (respecting the Western tuning system) or out of tune. Together with the experimental manipulations contrasting grammatical and ungrammatical target tones, the experimental trials thus consisted of sequences with 25% of the trials containing a grammatical in-tune tone, 25% an ungrammatical in-tune tone, 25% a mistuned tone that was based on the grammatical tone, and 25% a mistuned tone that was based on the ungrammatical tone. The data analyses are restricted to the in-tune target tones (grammatical, ungrammatical) as the mistuned tones represent foils to define the experimental task.

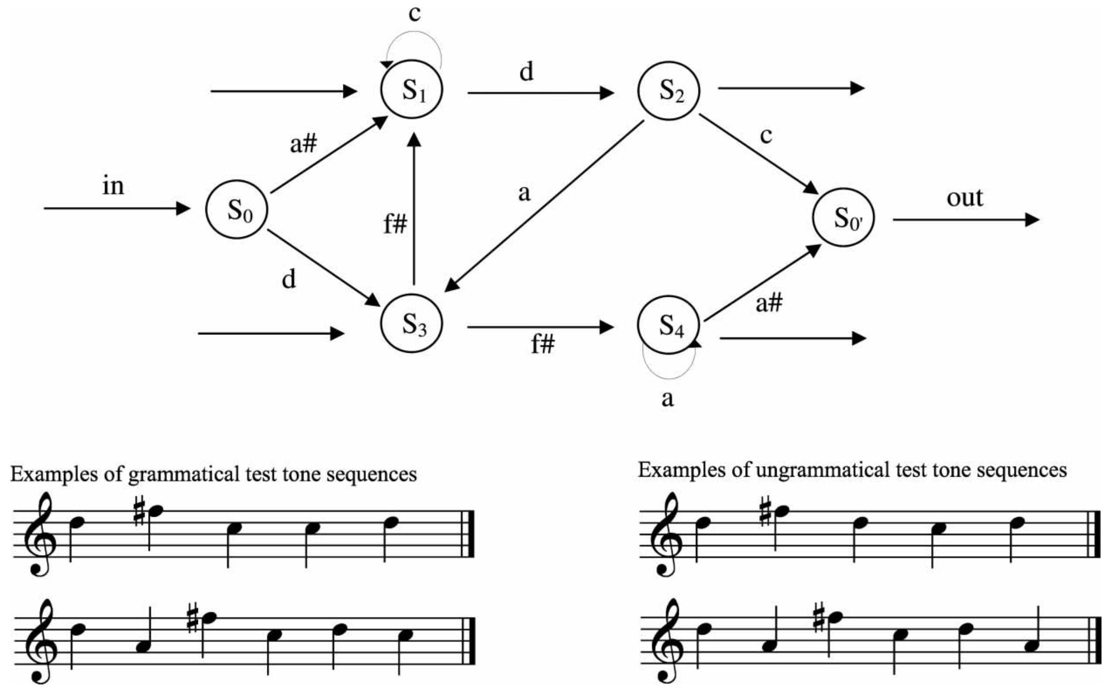

Figure 1. *Top: Finite-state grammar used for the construction of the tone sequences from Poulin-Charronnat et al., 2009. Bottom: Two examples of grammatical test sequences (left) and their ungrammatical counterpart (right).*

speed, we analysed grammatical exposure and test sequences as well as ungrammatical test sequences for a series of characteristics that have been described as relevant in previous artificial grammar research and ran regression analyses to predict participants' response time patterns.

EXPERIMENT 1

Method

Participants
Thirty-two students of Lyon University participated in the experiment; 16 were attributed to the control group (no exposure phase) and 16 to the exposure group (with exposure phase). Number of years of musical training as measured by years of instrumental instruction ranged from 0 to 12 in both groups, with means of 2.31 (±3.74) and 1.91 (±2.99) for control and exposure groups, respectively (both groups had a median of 1). None of the participants reported to have absolute pitch.

Material
The material was based on the finite-state grammar displayed in Figure 1 and was associated with five tones (i.e., *a, a#, c, d, f#*).[3] This finite-state grammar was created on the basis of

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[3] The five tones defined a nondiatonic set. One might argue that these tones belong to the key of *g* minor, even if the tonic *g* (i.e., the most important and most frequently used tone of a key) is absent. To investigate whether grammatical and ungrammatical sequences might differ in the tonal stability of the used tones, we attributed to each tone a value reflecting their respective role in the tonal hierarchy of a minor key (these values were taken from Krumhansl, 1990, Table 2.1, p. 30). The average of these values (summed over tones in each sequence) did not differ between grammatical and ungrammatical test sequences (16.35 and 16.43, respectively; $p = .595$). Consequently, ungrammatical items cannot be detected because of the use of less stable tones (in reference to g minor).

previously used grammars (e.g., Altmann et al., 1995). Because of the importance of anchor points (i.e., first and last tones of sequences; see A. S. Reber, 1967; A. S. Reber & Lewis, 1977) and aiming to test for learning beyond first and last events, we adapted the grammar to have four possible starting events (*a#*, *c*, *d*, *f#*) and five possible final events (*a*, *a#*, *c*, *d*, *f#*). A grammatical sequence was constructed by following the flow chart indicated by the arrows in the schema (Figure 1): For example, one can enter the grammar on the left by using the middle arrow and turn left (starting tone *a#*), followed by the optional loop (leading to *c*–*c*), the next arrow adds the *d*, and the system can be quit with the upper exit arrow (resulting in the grammatical sequence: *a#*–*c*–*c*–*d*). A total of 37 grammatical exposure, 37 grammatical test, and 37 ungrammatical test sequences were used (see Appendix and Figure 1). Sound examples can be found at: http://olfac.univ-lyon1.fr/bt-sound

Ungrammatical test sequences were created by changing one tone in each of the grammatical test sequences (e.g., *d*–*f#*–*c*–*c*–*d* → *d*–*f#*–*d*–*c*–*d*). The changed tone was part of the system's tone set (i.e., no new tone was introduced) and did not create new bigrams with preceding or following tones (a bigram is defined as a tone pair, such as *c*–*d*). Thus, the bigrams around the ungrammatical tone also occurred in grammatical exposure sequences and grammatical test sequences. The ungrammatical sequences respected frequency distributions of tones and bigrams (see Tables 1 and 2), but they introduced new trigrams of tones (defined as a three successive tones, such as *d*–*a*–*a*).

Table 1. *Frequencies of occurrence of tones in grammatical exposure, grammatical test, and ungrammatical test sequences*

		Test sequences	
Tones	*Exposure sequences*	*Grammatical*	*Ungrammatical*
c	48	51	39
d	48	49	50
f#	42	42	42
a	53	50	60
a#	16	16	17

Table 2. *Frequencies of occurrence of bigrams of tones in grammatical exposure, grammatical test, and ungrammatical test sequences*

		Test sequences	
Tones	*Exposure sequences*	*Grammatical*	*Ungrammatical*
aa	15	12	24
da	25	26	21
f#a	13	12	15
aa#	4	5	9
f#a#	2	5	2
a#c	8	1	1
cc	24	17	7
dc	3	10	12
f#c	7	13	9
a#d	2	5	5
cd	21	24	27
f#d	15	8	9
af#	25	26	19
df#	6	7	11

For grammatical and ungrammatical test sequences, several descriptors that have been shown to influence implicit learning of letter strings and learning of melodies (notably, melodic contour, see Krumhansl, 1991) were computed for the target tone. For the first four descriptors tested here, the differences between grammatical and ungrammatical test sequences were not significant:

1. The element frequency (Hunt & Aslin, 2001), which corresponds to the frequency of occurrence of all tones in the exposure sequences transferred to the target tones, was comparable between grammatical and ungrammatical sequences, 45.73 versus 46.30, $t(36) < 1$, $p = .71$.
2. The frequency of occurrence of the repetition of the target tone (in positions $n - 1$ and $n - 2$) was comparable between grammatical and ungrammatical sequences, 0.51 versus 0.32, $t(36) = 1.02$, $p = .31$.
3. The melodic contour created by the tones preceding the target (in positions $n - 1$ and $n - 2$) and the target (i.e., creating an up, down, or static movement) did not differ significantly between grammatical and ungrammatical sequences, $t < 1$, $p = .88$.

4. Concerning the anchors, the frequencies of occurrence of the tones in the first position of the exposure sequences that we transferred to the first tones of grammatical and ungrammatical test sequences were comparable between grammatical and ungrammatical test sequences, 9.16 versus 9.24, $t = -1.78$, $p = .08$; we did not further analyse for effects of final anchors as the target tone occurred in the last position only in 8 trials (out of 37).
5. The bigram frequency (Hunt & Aslin, 2001), which corresponds to the frequency of bigram occurrence in exposure sequences transferred to the bigrams of grammatical and ungrammatical test sequences (with the target being the second tone), was greater for grammatical than for ungrammatical sequences, 20.22 versus 14.97, $t(36) = 2.75$, $p < .01$.
6. The trigram frequency (Hunt & Aslin, 2001), which corresponds to the frequency of trigram occurrence in the exposure sequences transferred to the trigrams of grammatical and ungrammatical test sequences (with the target being the third tone), was greater for the grammatical than for the ungrammatical sequences, 15.54 versus 0.51, $t(36) = 8.49$, $p < .001$.
7. The associative chunk strength (ACS), which indicates the overlap of both bigrams and trigrams of tones between exposure and test sequences (Knowlton & Squire, 1994, 1996; see Meulemans & van der Linden, 1997, for a detailed description of ACS computation), was stronger for grammatical test sequences than for ungrammatical test sequences, 17.88 versus 7.74, $t(36) = 6.97$, $p < .001$.
8. The chunk novelty, which corresponds to the number of new chunks present in the test sequences compared to that in the exposure sequences (Johnstone & Shanks, 1999; Meulemans & van der Linden, 1997), was lower for grammatical than for ungrammatical sequences, 0.05 versus 0.89, $t(36) = -13.64$, $p < .001$.
9. The novel chunk position (NCP), which corresponds to the measure of how many times bigrams and trigrams that were part of the exposure sequences occurred in novel positions within test sequences (Johnstone & Shanks, 1999), was lower for grammatical than for ungrammatical sequences, 0.19 versus 0.62, $t(36) = -3.81$, $p < .001$.
10. The first-order and second-order transitional probabilities (TP1, TP2), which correspond to the probability of occurrence of a tone (e.g., *f#*) after a given tone (e.g., *a*) or bigram of tones (e.g., *d*–*a*), respectively, were calculated as follows: For TP1, the frequency of a pair AB was divided by the absolute frequency of A in the exposure sequences (Saffran et al., 1996); for TP2, the frequency of the triplet ABC was divided by the absolute frequency of AB in the exposure sequences. TP1 and TP2 were greater for the targets in the grammatical sequences than for those in the ungrammatical sequences: .39 versus .29, $t(36) = 2.74$, $p < .01$, and .70 versus .02, $t(36) = 10.84$, $p < .001$, respectively.

Each tone was played with a piano timbre and sounded for a duration of 500 ms. In the tone sequences, the intertone interval was set to 0 ms. All sequences contained either five or six tones and thus lasted for 2,500 ms or 3,000 ms, respectively. Target tones were the tones creating the grammatical violation in the ungrammatical sequences and the tones in the same temporal position in the corresponding grammatical test sequences. To create out-of-tune targets, which were needed for the priming task, tones were mistuned by −52 cents. This extent of mistuning was chosen to make the to-be-detected mistuning relatively salient (note that one semitone corresponds to 100 cents); it corresponds to the largest change in cents previously used by Warrier and Zatorre (2002). The experiment was run with PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993).

Procedure

The exposure group first realized the memory task (i.e., the exposure phase) and then the priming task. In the memory task, the grammatical exposure sequences were presented three times in random order, and participants indicated whether they heard a given sequence for the first time.

They thus responded after each sequence. The control group only worked on the priming task. For the priming task, participants judged as quickly and accurately as possible whether the target was in tune or out of tune by pressing one of two keys on a computer keyboard. Since the target occurred at various positions inside the tone sequence, visual information was displayed on the screen (see Tillmann & Marmel, 2009, introducing this online priming paradigm with musical material). Each visual cue was synchronized with the tone onset: The target was indicated by a question mark (referring to the question "is this tone in tune or out of tune?"), the tone preceding the target was indicated by a visual warning signal (allowing for response preparation), and the other tones were indicated by a white circle (Figure 2). A fixation cross preceded each sequence and created an interonset interval of 1,000 ms with the first visual cue that was associated with a tone. The tone sequences were always presented entirely. The in-tune/out-of-tune priming task and the visual indications were explained to the participants with examples. For training on the in-tune/out-of-tune judgements, participants then realized this task with four sequences. These training sequences were grammatical sequences randomly selected from the exposure material, and they contained two in-tune and two out-of-tune targets, with 1 five-tone and 1 six-tone sequence each. After this training, participants realized the task on the 148 experimental sequences (74 test sequences presented with in-tune and out-of-tune targets), which were presented in random order for each participant. Incorrect responses were accompanied by an alerting feedback signal.

Data analyses

As in-tune targets were correctly tuned tones at the expected pitch height, and out-of-tune targets represented foils, which were defined only for the purpose of the experimental task, analyses focused on in-tune targets, as previously done in musical priming research (e.g., Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2003). Participants were excluded from the analyses when overall accuracy was below 60% or when accuracy for in-tune targets was below 40%.

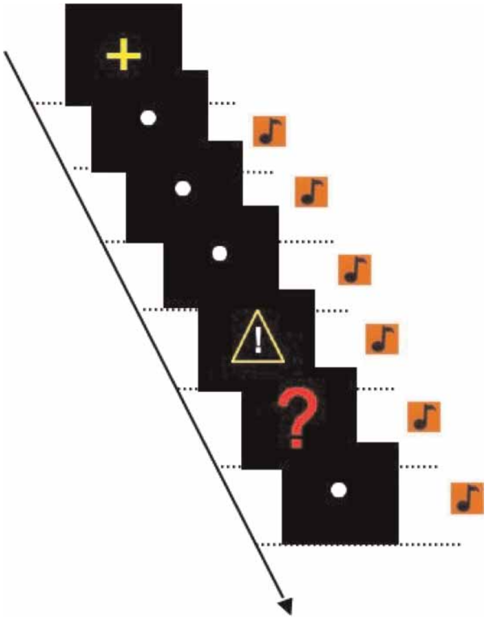

Figure 2. *Schematic presentation of an experimental trial (visual information on the left, tone sequence on the right) presented on a time line: The fixation cross preceded the sequence, then each visual cue was synchronized to the onset of a tone. In the present example, the to-be-judged target is in the fifth position. Visual information was presented in the centre of the computer screen. Tone sequences were presented auditorily over headphones. To view a colour version of this figure, please see the online issue of the Journal.*

To further investigate the features that might explain test performance, we ran step-by-step regression analyses (criterion for inclusion, $p < .05$) on participants' response times (on items) and the values of selected descriptors. Among all the descriptors reported in the "Material" section, we selected the descriptors that differed significantly between grammatical and ungrammatical test sequences (bigram frequency, trigram frequency, chunk novelty, novel chunk position, ACS, TP1, TP2). We ran correlations between these selected descriptors (Table 3), and to avoid collinearity we considered further only descriptors with correlations inferior to .70 in the regression analyses. For exposure and control groups separately, we ran a regression analysis with bigram

Table 3. *Correlations between the descriptors showing a significant difference between grammatical and ungrammatical sequences*

	ACS	*TP1*	*TP2*	*Chunk novelty*	*Bigram frequency*	*Trigram frequency*
ACS						
TP1	.837**					
TP2	.890**	.537**				
Chunk novelty	−.602**	−.305**	−.821**			
Bigram frequency	.848**	.996**	.544**	−.283*		
Trigram frequency	.900**	.517**	.975**	−.730**	.533**	
NCP	−.402**	−.480**	−.247*	.052	−.508**	−.225

Note: ACS = associative chunk strength. TP1 = first-order transitional probability. TP2 = second-order transitional probability. NCP = novel chunk position.
$^{*}p < .05$. $^{**}p < .01$.

frequency, trigram frequency, and NCP and a regression analysis with TP1, TP2, and NCP. While the first regression analysis tested for the influence of frequency of occurrence of bigrams and trigrams, the second analysis using TP1 and TP2 tested whether participants also consider the frequency of occurrence of the first item (in a bigram) or the first two items (in a trigram) to form their expectations.

Results

One participant of the exposure group was excluded from the analyses because of low accuracy. For the remaining participants, accuracy for in-tune and out-of-tune targets was, respectively, 79.19% and 79.69% for the control group and 80.96% and 86.20% for the exposure group. For the in-tune targets, percentages of correct responses and correct response times were analysed with two analyses of variance (ANOVAs) with item type (grammatical/ungrammatical) as within-participant factor and group (control/exposure) as between-participants factor.

For accuracy and correct response times (Table 4, Figure 3), the interaction between item type and group was significant, $F(1, 29) = 7.78$, $p = .009$, $MSE = 29.78$, and $F(1, 29) = 5.41$, $p = .03$, $MSE = 1{,}027.44$, respectively. For the exposure group only, correct responses were more numerous, and response times were faster for grammatical than for ungrammatical items, $F(1, 29) = 9.65$, $p = .004$, and $F(1, 29) = 14.65$, $p < .0001$ (control group: $p\text{s} > .43$). No other effects were significant, except for a main effect of item type for response times, $F(1, 29) = 10.07$, $p = .004$, $MSE = 1{,}027.44$.

Table 4. *Average percentages of correct responses for grammatical and ungrammatical in-tune targets for Experiment 1 and Experiment 2*

		Item type	
	Group	*Grammatical*	*Ungrammatical*
Experiment 1	Control	78.42 (3.55)	79.96 (4.03)
	Exposure	84.06 (1.98)	77.87 (2.54)
Experiment 2		85.35 (1.92)	75.59 (2.94)

Note: In-tune targets for Experiment 1 for control and exposure groups. Standard errors are indicated in parentheses.

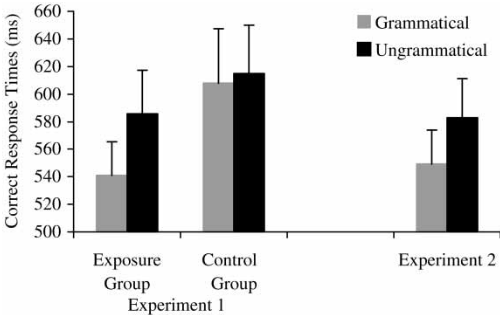

Figure 3. *Correct response times for grammatical and ungrammatical target tones obtained in Experiment 1 (for exposure and control groups) and in Experiment 2. Error bars indicate between-participants standard errors.*

Additional ANOVAs on correct responses and response times integrating item length (5-tone/6-tone sequences) confirmed that the interaction between group and item type and particularly the learning in the exposure group was observed for both 5- and 6-tone sequences. These analyses did not reveal an interaction between item length and item type or group (all ps $> .47$). Only the main effect of item length was significant, with more correct responses (82.33%), $F(1, 29) = 7.55$, $p = .01$, $MSE = 89.01$, and faster response times (574 ms) for 6-tone sequences, $F(1, 29) = 7.62$, $p = .01$, $MSE = 3{,}207.18$, than for 5-tone sequences (77.77%, 603 ms). Over both lengths, item analysis on response times confirmed the difference between grammatical and ungrammatical items for the exposure group, $t_2(36) = 2.1$; $p = .006$.

For the exposure group, the first regression analysis revealed that only trigram frequency had a significant influence on performance, $r(72) = -.26$, $t = -2.3$, $p = .02$, and the second regression analysis revealed that only TP2 had a significant influence on performance, $r(72) = -.26$, $t = -2.249$, $p = .03$. For the control group, no descriptors reached the criterion to be included in the regression analyses, indicating that for the control group none of the descriptors influenced performance.

For the exposure group, correct responses in the memory phase were at 62.16% ($SD = 6.88$), but memory performance did not correlate with response time differences between grammatical and ungrammatical test items, $r(13) = .07$. Finally, the grammaticality effect did not correlate with the number of years of musical instruction, $r(13) = .05$.

Discussion

Experiment 1 combined implicit learning and priming paradigms to investigate whether newly acquired structure knowledge allows listeners to develop auditory expectations for future events. After exposure to grammatical tone sequences, priming task performance was faster and more accurate for target tones respecting the grammar than for target tones violating the grammatical structure. In contrast, the control group, which was lacking the exposure phase, did not show this processing advantage.

The outcome suggests that listeners' artificial grammar knowledge acquired during the exposure phase facilitates the processing of grammatically expected tones in comparison to ungrammatical, unexpected tones. The artificial grammar knowledge was acquired without any motor response associated to the individual tones. The data thus point out the perceptual learning of artificial grammar structures in the auditory modality.

The subtle ungrammaticalities of the test sequences together with the regression analyses suggest that participants' knowledge went beyond the level of bigrams and included knowledge about trigram frequency as well as transitional probabilities of second order. Notably, higher transitional probabilities led to faster response times. Artificial language experiments have shown that participants can learn first-order transitional probabilities, allowing them to succeed in word/nonword judgements, but their influence on online perceptual expectancy formation had not been shown yet. SRT paradigms have shown the learning of second-order conditional sequences, and thus participants needed to take into consideration two preceding events to predict the next event (e.g., Destrebecqz & Cleeremans, 2001). Our findings now further show that participants can learn second-order transitional probabilities, which then allow perceptual expectancy formation, and this without the contribution of motor learning.

The newly acquired knowledge influences the in-tune judgements of target tones indirectly since participants were not required to judge grammaticality or to explicitly predict the next event. The priming task provides a relevant tool to investigate implicit artificial grammar knowledge without revealing the rule-governed nature of the stimuli to participants or encouraging explicit feature search (i.e., in agreement with Vinter & Perruchet, 1999). It further allows the use of exactly the same test instructions for participants of both exposure and control groups, which has not been the case for studies using grammaticality judgements and which has raised some criticisms (R. Reber & Perruchet, 2003).

It might be argued that our present finding cannot conclude for implicit learning and knowledge because (a) we did not test for implicit versus explicit knowledge, as has been previously done in artificial grammar research, and (b) the memory task in the exposure phase might have encouraged participants to search for structural regularities to obtain better memory scores, leading them to acquire at least partial explicit knowledge. In artificial grammar research, the implicit nature of the acquired knowledge has been investigated with participants' confidence judgements on the given grammaticality judgements (e.g., zero-correlation criterion or above-chance performance in grammaticality judgements for guessing responses; Dienes, 2008). In our study, participants were never told about the grammar. Therefore, it was impossible to collect confidence judgements investigating the part of explicit knowledge in grammaticality judgements. Addressing the second point of the criticism raised here above, Experiment 2 omitted the memory task—even if memory tasks were commonly used in artificial grammar studies. In the exposure phase, participants were now asked to indicate after each sequence whether a mistuned tone had occurred. This detection task required attentive listening without calling for memorization and without explaining structural features of the sequences to the participants. In addition, Experiment 2 reduced the exposure phase from three to two presentations of the grammatical sequences, as had been done in the study using explicit grammaticality judgements (Poulin-Charronnat et al., 2009). The goal was to investigate whether the same amount of exposure, which allowed for successful grammaticality judgements in the test phase, is sufficient to allow for perceptual expectancy formation.

EXPERIMENT 2

Method

Participants

Twenty-four students of the University of Burgundy participated in Experiment 2. Number of years of musical training as measured by years of instrumental instruction ranged from 0 to 10, with a mean of 1.00 (±2.59) and a median of 0. None of the participants reported to have absolute pitch.

Material

The material of Experiment 1 was used. In addition, for the purpose of the task in the exposure phase, we constructed for each of the 37 grammatical exposure sequences a second version of each sequence that included an out-of-tune tone (i.e., mistuned by −52 cents as in Experiment 1). The position of this out-of-tune tone varied between the sequences to cover the same positions as those in the sequences of the test phase. The experiment was run with PsyScope (Cohen et al., 1993).

Procedure

In the exposure phase, the 37 grammatical exposure sequences with all tones being in tune and the 37 counterparts including one out-of-tune tone were presented auditorily in random order. After each sequence, participants indicated whether the sequence contained an out-of-tune tone or not. No error feedback was given. The second phase with the priming task was as described in Experiment 1.

Data analyses

Data analyses were as described in Experiment 1.

Results

Two participants were excluded from the analyses because of low accuracy. For the remaining participants, accuracy for in-tune and out-of-tune targets was, respectively, 80.39% and 79.70%. For in-tune targets, percentages of correct responses and correct response times (Table 4, Figure 3) were analysed with two ANOVAs with item type (grammatical/ ungrammatical) as within-participant factor.

For accuracy and correct response times, the main effect of item type was significant, $F(1, 21) = 22.51$, $p < .001$, $MSE = 46.57$, and $F(1, 21) = 6.08$, $p = .02$, $MSE = 2{,}046.20$, respectively. Correct responses were more numerous, and response times were faster for grammatical than for ungrammatical tones. Supplementary ANOVAs on correct responses and response times that integrated Item length (5-tone/6-tone sequences) as an additional within-participant factor confirmed the main effects of item type and revealed that the difference between grammatical and ungrammatical items was not modified by item length (ps $> .18$). Also, there were no main effects of item length (ps $> .28$). Over both lengths, item analysis on response times confirmed the difference between grammatical and ungrammatical items, even if it just felt short of significance, $t_2(36) = 1.79$, $p = .08$.

The regression analyses confirmed the results of the exposure group of Experiment 1. The first regression analysis (on bigram frequency, trigram frequency, and NCP) revealed that only trigram frequency had a significant influence on performance, $r(72) = -.30$, $t = -2.65$, $p = .01$. In the second regression analysis (i.e., TP1, TP2, and NCP), only TP2 had a significant influence, $r(72) = -.25$, $t = -2.16$, $p = .03$.

Finally, a 2 × 2 ANOVA with item type as within-participant factor and experiment (Experiment 1/Experiment 2) as between-participants factor showed that the priming effects of the exposure groups in Experiments 1 and 2 did not differ: Only the main effect of item type was significant ($p < .001$); neither the main effect of experiment nor its interaction with item type (ps $> .57$) was significant.

For the out-of-tune detection task in the exposure phase, participants reached an accuracy level of 85.69 % ($SD = 7.29$).

Discussion

Experiment 2 replicated the priming effect for the newly acquired tone material, as observed in Experiment 1. It further confirmed that participants' response patterns can be predicted by the materials' characteristics beyond the bigram level, notably by trigram frequency and transitional probabilities of second order. The comparison of the data sets of the two experiments suggests that the memory task in Experiment 1 was not creating the priming effect by encouraging participants to search for structural features in the sequences. In Experiment 2, in exposure and test phases, participants judged the tuning of the tones: first to detect mistuned tones in the exposure sequences and then to make speeded accuracy judgements on indicated target tones inside the test sequences.

In contrast to commonly used testing procedures in artificial grammar experiments, participants were never told about the underlying grammar (as suggested by Vinter & Perruchet, 1999). It thus seems unlikely that participants would have applied strategies to search for structures and rules. Furthermore, the tasks focused locally on a tone, and the requested speeded response judgements (i.e., whether the tone is in tune or out of tune) can be made independently of the structural regularities of this artificial system. This is comparable to psycholinguistic research using the lexical decision task to investigate semantic or syntactic priming: A letter string is a word or a nonword (in itself), and it is thus not necessary to consider syntactic or semantic structures to make this judgement (i.e., these structures influence task performance indirectly). One might rather wonder whether participants might try to develop explicit expectations about *when* in the sequence the to-be-judged target tone will occur (rather than *which* tone will occur). However, the tested positions were random from trial to trial, and participants were informed only with one event preceding the target ($n - 1$) thanks to the visual warning signal. The varying positions, the short notice, and the requested speeded response should further discourage participants to develop explicit strategies searching for structures in the tone sequences.

GENERAL DISCUSSION

Perceivers become sensitive to the structure of the environment by mere exposure; they use this knowledge for efficient interaction, notably by developing expectations for structurally probable events, leading to facilitated processing for expected events. The priming paradigm is an experimental tool that has allowed testing perceivers' expectations for structured material, such as language or music (see McNamara, 2005, and Tillmann, 2005, for reviews). Our present study investigated whether similar perceptual expectations can be developed for structure knowledge freshly acquired in the experimental session.

Previous research has shown that listeners can acquire new structure knowledge in the laboratory, such as structures based on artificial grammars and artificial languages. The implicit learning processes are not restricted to visual information (e.g., letter sequences used in the seminal studies by A. S. Reber, 1967), but apply also to auditory information, as, for example, tone sequences (e.g., Altmann et al., 1995; Saffran et al., 1999). Listeners acquire knowledge about the artificial structures by mere exposure and can then distinguish above-chance new grammatical sequences from ungrammatical sequences (or words from nonwords). However, the required judgements have been based on the entire sequences and, in addition, requested to inform participants about the underlying systems (grammar or language).

Our study used the priming task in the testing phase and showed that the newly acquired knowledge about the tone structures of the artificial grammar influenced the speed of target tone processing. Target tone processing was facilitated when the target respected the underlying grammatical structure in contrast to when it violated this structure. The data suggest that listeners' knowledge, which allowed differentiating grammatical and ungrammatical items in grammaticality judgements (Poulin-Charronnat et al., 2009), allows also for expectancy formation for upcoming tones. Based on the newly acquired tone structure knowledge, listeners develop perceptual expectations on future tones, notably for tones respecting the underlying grammatical structure.

The controlled construction of the material used here, and notably of the ungrammatical sequences, suggests that the knowledge acquired by the listeners goes beyond the simple detection of a new, previously unheard bigram, of changes in contour, or of tone repetitions. Our material and the priming paradigm revealed that listeners can learn and perceive structures in tone materials that are more complex than previously shown. For example, Krumhansl (1991) highlighted the importance of melodic contour for memory of music, while Smith and Mathews (1969) showed the importance of simple repetitions of tone patterns for the learning of melodies that participants had to classify as grammatical or random. In our study, melodic contour and repetitions cannot explain participants' performance after exposure as these features did not differ between grammatical and ungrammatical test items. The acquired knowledge thus needed to include knowledge about higher structure levels. Our findings suggest that participants have learned information about trigrams and about patterns of transitional probabilities including three tones (i.e., how strongly the third tone is expected given the first two tones): The higher the second-order transitional probabilities, the faster the response times. Our finding extends the previously shown influence of first-order transitional probabilities on response times in the visual modality: Fiser and Aslin (2002) have reported that participants use higher order statistics (i.e., first-order transitional probabilities) when information in joint probabilities (i.e., bigram frequency normalized by the total frequency of bigrams in the sample) did not differ. Second-order transitional probabilities have been also used in previous SRT paradigms, which, however, included the contribution of motor learning (e.g., Destrebecqz & Cleeremans, 2001).

Our study shows that listeners acquire structure knowledge allowing the formation of expectations for future tones in the sequences. The used test sequences tested for pitch expectations on the specific pitch height of the tones in the set selected for the grammar. Because of the phenomenon of octave equivalence (i.e., the perceived similarity of tones separated by an octave, such as a low *c3* and a higher *c4*), future research will need to test whether participants' expectations are restricted to this specific pitch height or might generalize to pitch chroma and thus represent facilitated processing for the target tone presented in another octave.

In our material, the tone set respected the chromatic tone system of Western tonal music, which allowed participants to perform the priming task (i.e., in-tune/out-of-tune judgements). Over exposure, participants learned the new structural relations between these tones as defined by the artificial grammar. Future research might investigate whether participants' familiarity with the individual items used (here the chromatic tones) might influence learning of new structures or the level of higher order statistics. The variety of material for which participants have been shown to learn statistics (also including synthesized timbres not previously encountered) suggests that learning persists (see Loui & Wessel, 2008, for a first attempt using material based on a Bohlen–Pierce scale and tested with familiarity judgements).

Our present finding makes a significant contribution to our understanding of perceivers' structure learning and its influence on perception. While previous studies using the SRT paradigm have been restricted by the use of repeated, fixed-sequence patterns, the contribution of motor learning, or the use of random test patterns (or a combination of these aspects), our present study used new grammatical sequences at test, and the exposure phase was based on mere perceptual observation. Our finding, based on an artificial grammar with tones, suggests that structured knowledge can be acquired via perceptual learning only (i.e., without motor learning). Future research might take advantage of combining the SRT procedure with an indirect measure, as the priming task used here. Instead of making a direct motor response to a light (i.e., detection), participants could make a speeded judgement on another perceptual dimension of the item occurring in the next location. This could be a two-alternative forced-choice identification judgement (e.g., on luminosity or colour) as used here or could be combined with a perceptual clarification procedure (e.g., how much luminosity is necessary to detect the next item) to further investigate the influence of structured knowledge on low-level perceptual processes.

Furthermore, the indirect methods introduced here might provide a more sensitive testing of acquired knowledge and of possible transfers than has been allowed by explicit tasks (Cleeremans & Jiménez, 2002; Helman & Berry, 2003). The use of the priming task allows taking advantage of the power of implicit processes in the testing phase of implicit learning research. For the exposure phase, it has been previously shown that the incidental (implicit) acquisition of the grammatical structures is more powerful than the explicit acquisition of the same structures (e.g., Fletcher et al., 2005). The data of our study showed that an implicit testing approach allows the acquired structure knowledge to be revealed, as reflected in the facilitated processing for grammatical items over ungrammatical items. As discussed above, the implicit priming paradigm revealed learning of more complex features than previously shown with explicit tasks (e.g., tone repetition, Smith & Mathews, 1969). Based on numerous researches showing that implicit tests are more sensitive (e.g., Cleeremans & Jiménez, 2002; Schacter & Buckner, 1998), we make the hypothesis that the priming task should allow providing evidence for implicit knowledge of more complex structures than had been shown with explicit grammaticality judgements. Similarly, Kuhn and Dienes (2005) using complex transformation rules have revealed differences in the perception of correctly and incorrectly constructed sequences with liking judgements, but not with grammaticality judgements (see, however, Desmet, Poulin-Charronnat, Lalitte, & Perruchet, 2009). In contrast to liking judgements, which are subjective judgements on the entire sequence and for which no correct/false responses can be defined, the priming task requests participants to make a speeded objective identification judgement. The response times to the target provide insight into the processing of individual events and the influence of grammaticality.

Our study with artificial tone structures imitates the natural phenomenon of tonal acculturation and musical expectancy formation inside the lab: Nonmusicians acquire implicit knowledge of the Western tonal system by mere exposure to musical pieces obeying this system. Musical priming studies have shown the influence of this musical knowledge on the development of musical expectations and on speed of processing: Musical event processing (i.e., tone, chord) is faster for structurally related events that occur at expected pitch heights and time points (e.g., Bigand et al., 2003; Tillmann & Lebrun-Guillaud, 2006). The beneficial influence of auditory expectations has been shown not only for response times, supposed to reflect processing complexity, but also more specifically for low-level, perceptual processes. For example, pitch discrimination is enhanced when the to-be-processed tone occurs at the expected pitch height (Marmel et al., 2008) and the expected time point (Bausenhart, Rolke, & Ulrich, 2007). More generally, processing facilitation has been observed thanks to bottom-up expectations based on characteristics of the experimental session (i.e., directly preceding cues or high probabilities of occurrence; e.g., Greenberg & Larkin, 1968) and to top-down expectations based on knowledge acquired outside the lab (i.e., language, music). Our study showed that top-down expectations based on newly acquired structure knowledge (i.e., acquired in the lab) influences processing speed (i.e., response times); it remains to be shown whether they can go beyond this influence and are powerful enough to facilitate early perceptual processing steps (e.g., pitch processing).

A future direction of this research line is the combination of the behavioural approach used here with computational simulations. For Western tonal music, computational approaches on knowledge acquisition have been proposed previously to simulate nonmusicians' acquisition via mere exposure (e.g., Pearce & Wiggins, 2006; Tillmann, Bharucha, & Bigand, 2000). The computational models were first trained with exemplars of Western tonal music and then used to simulate behavioural data of Western listeners for tonal material. Unsupervised learning mechanisms were successful to simulate parsimonious knowledge representations of listeners' musical knowledge (see Tillmann et al., 2000, for the Western tonal system; Krumhansl, Toivanen, Eerola, Jarvinen, & Louhiviori, 2000, for Finnish music; and Curtis & Bharucha, 2009, for Indian music). Focusing on melodic expectations, the model by Pearce and Wiggins (2006) uses subsystems that are first trained on various features (e.g., onset, duration, pitch, interval, contour, and combinations thereof) and *n*-gram levels and that are then combined to maximize the fit with experimental data (recently combined with event-related potential, ERP, data; see Pearce et al., 2009). Future research on implicit learning of artificial tone material and/or new tone/musical systems might apply similar training procedures to the simulation of artificial knowledge acquisition and expectations. This might allow the development of modelling approaches, which have been previously proposed for light sequences or syllables sequences (e.g., SRN, PARSER), to auditory, nonverbal materials with their specific characteristics (e.g., intervals).

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APPENDIX

Sequences used

Grammatical exposure sequences	*Grammatical test sequences*	*Ungrammatical test sequences*
a#−c−c−c−d	a#−d−a−f#−a	a#−d−a−a−a
a#−c−c−d−c	a#−d−a−f#−a#	a#−d−a−a−a#
a#−c−d−a−f#	c−c−c−d−c	c−d−c−d−c
a#−d−a−f#−d	c−c−d−a−f#	c−c−d−a−a
c−c−c−c−d	c−d−a−f#−a	c−d−a−a−a
c−d−a−f#−d	c−d−a−f#−a#	c−d−a−a−a#
d−a−f#−a−a	d−a−f#−c−d	f#−a−f#−c−d
d−a−f#−a−a#	d−a−f#−d−c	f#−a−f#−d−c
d−f#−d−a−f#	d−f#−a−a−a	d−f#−a−f#−a
f#−a−a−a−a	d−f#−a−a−a#	d−f#−a−f#−a#
f#−a−a−a−a#	d−f#−c−c−d	d−f#−d−c−d
f#−c−c−c−d	d−f#−c−d−c	d−f#−c−d−f#
f#−d−a−f#−a	f#−c−c−d−c	f#−d−c−d−c
f#−d−a−f#−a#	f#−c−d−a−f#	f#−c−d−a−a#
f#−d−a−f#−d	a#−c−d−a−f#−a#	a#−c−d−a−a−a#
a#−c−c−c−c−d	a#−d−a−f#−a−a	a#−d−a−a−a−a
a#−c−c−c−d−c	a#−d−a−f#−a−a#	a#−d−a−a−a−a#
a#−c−c−d−a−f#	a#−d−a−f#−d−c	a#−d−a−f#−d−f#
a#−c−d−a−f#−a	c−c−c−c−d−c	c−c−d−c−d−c
a#−c−d−a−f#−d	c−c−c−d−a−f#	c−d−c−d−a−f#
a#−d−a−f#−c−d	c−c−d−a−f#−a#	c−c−d−a−a−a#
c−c−c−c−c−d	c−d−a−f#−a−a	c−d−a−f#−a−f#
c−c−d−a−f#−a	c−d−a−f#−a−a#	c−d−a−a−a−a#
c−c−d−a−f#−d	c−d−a−f#−d−c	c−d−a−f#−d−f#
c−d−a−f#−c−d	d−a−f#−a−a−a#	d−a−f#−a−f#−a#
d−a−f#−a−a−a	d−a−f#−c−c−d	f#−a−f#−c−c−d
d−a−f#−d−a−f#	d−a−f#−c−d−c	d−a−f#−c−d−a
d−f#−a−a−a−a	d−f#−a−a−a−a#	d−f#−a−f#−a−a#
d−f#−c−c−c−d	d−f#−c−c−d−c	d−f#−c−c−d−f#
d−f#−c−d−a−f#	d−f#−d−a−f#−d	d−f#−a−a−f#−d
d−f#−d−a−f#−a	f#−a−a−a−a−a	f#−a−a−a−f#−a
d−f#−d−a−f#−a#	f#−c−c−c−c−d	f#−d−c−c−c−d

(*Continued on next page*)

APPENDIX (*Continued.*)

Grammatical exposure sequences	*Grammatical test sequences*	*Ungrammatical test sequences*
f#–a–a–a–a–a#	f#–c–c–d–a–f#	f#–d–c–d–a–f#
f#–c–c–c–d–c	f#–c–d–a–f#–a	f#–c–d–a–a–a
f#–c–d–a–f#–d	f#–c–d–a–f#–a#	f#–c–d–a–a–a#
f#–d–a–f#–a–a	f#–d–a–f#–c–d	f#–a–a–f#–c–d
f#–d–a–f#–a–a#	f#–d–a–f#–d–c	f#–a–a–f#–d–c