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Working Memory for Tonal and Atonal Sequences during a Forward and a Backward Recognition Task

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WE INVESTIGATED WORKING MEMORY (WM) PERFORMANCE for tone sequences that either respected musical regularities (tonal sequences) or did not (atonal sequences) using a forward and a backward recognition task. Participants indicated whether two sequences were the same or different, with "same" being defined as all tones played correctly in either the same order (forward task) or backward order (backward task). For the forward task, nonmusician and musician participants showed better performance for tonal than for atonal sequences, therefore supporting the hypothesis that musically structured material increased WM performance during maintenance of tone information. For the backward task, neither nonmusicians nor musicians showed better performance for tonal compared to atonal sequences. Our findings suggest that musical structure influences WM for tones during maintenance (forward recognition task), but not during manipulation (backward recognition task).

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Key words: working memory for auditory material, musical structure, expertise, nonmusicians, musicians

Numerous studies have investigated working memory (WM) processes for verbal and visual materials (for an overview, see Baddeley, 2003), while those investigating auditory, nonverbal materials such as music remain relatively sparse and have emerged more recently (Deutsch, 1970; Gaab & Schlaug, 2003; Koelsch et al., 2009; Schulze, Zysset, Mueller, Friederici, & Koelsch, 2011; Semal, Demany, Ueda, & Halle, 1996; Williamson, Baddeley, & Hitch, 2010). Thus, WM for nonverbal auditory information is still not well understood. The present study investigated WM for tones. In particular, the potential influences of the following aspects on auditory WM were studied: (1) forward and backward recognition of tone information, as well as the influence of (2) sequence length and (3) structure of the to-be-remembered material.

Forward and Backward Recognition

Working memory enables temporally limited storage and maintenance (e.g., by active rehearsal) as well as processing or manipulating of information (Baddeley, 2003; Baddeley & Hitch, 1974). For example, while a forward digit span task only involves maintenance of information, a backward digit span task requires participants to reorder the digits, which thus requires maintenance and manipulation. Previous studies have shown that participants perform better during forward recall compared to backward recall tasks (e.g., Farrand & Jones, 1996; Hulme et al., 1997).

In addition, it has been suggested that different mechanisms underlie forward and backward recall. For example, Hulme et al. (1997) have shown that the word frequency effect (memory performance is better for high frequency words than for low frequency words) increases over serial positions during forward recall, but not during backward recall. Furthermore, a recent study on verbal WM has shown that the direction of recall (forward vs. backward) influences the following benchmark effects of WM: While stable influences of word length, acoustic confusability, irrelevant background speech, and concurrent articulation were observed during forward recall, these effects were less pronounced or missing during backward recall (Bireta et al., 2010). Therefore, WM required in forward and backward memory tasks seems to rely on different processes.

Up to now, maintenance and manipulation have been tested mostly with verbal or visual materials, except Dowling

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(1972) who used auditory, nonverbal stimuli (short tone sequences) to investigate forward and backward processing of tones with a recognition paradigm. Dowling investigated whether melodic transformations can be recognized by nonmusician listeners. The tone material consisted of atonal sequences; that is, sequences that do not respect regularities of Western tonal music. The musical transformations were inversions (turning the contour pattern of the melody upside down), retrograde transformations (playing the melody backwards) or retrograde inversions (playing the melody upside down and backwards). Participants were presented with a five-tone standard melody followed by a comparison melody that was either a correct or incorrect transposition (i.e., pitch shift) of one of the transformations. Nonmusicians (with an average level of musical experience of 2.25 years) recognized melodic transformations above chance, notably with best recognition for inversion, then retrograde, and finally, retrograde inversion. Therefore, findings by Dowling (1972) indicated that nonmusician participants were able to manipulate nonverbal auditory information in WM.

Sequence Length

Another factor that has been shown to influence WM is sequence length. WM limits restrict the amount of material that can be remembered; the longer the sequence (or the more events there are), the weaker the WM performance (Cowan, 2000). This is reflected, for example, in the word length effect (i.e., a smaller memory span for long words than for short words: Baddeley, Thomson, & Buchanan, 1975). In our study, we investigated the sequence length effect for auditory nonverbal (musical) material. Furthermore, we aimed to investigate whether effects of sequence length can be influenced by musical structure; that is, tonal structures respecting the musical system of participants' culture (here the Western tonal system).

Structure and WM

The structure of the to-be-remembered material has been reported to have an impact on WM capacity. Structured material can be beneficial for learning and memory (e.g., Deutsch & Feroe, 1981). Memory can be improved with stimulus-inherent structures; this has been shown for different materials; for example, for the recall of word lists (Savage et al., 2001; Tulving, 1962), spatial patterns (Bor, Duncan, Wiseman, & Owen, 2003), and auditorily presented digits (Bor, Cumming, Scott, & Owen, 2004).

For music, there is some evidence that musical structure and listeners' knowledge thereof influence short-term memory for tones and chords (i.e., maintenance). Musical material respecting the Western tonal system has an inherent structure; that is, subsets of tones are arranged according to complex rules and regularities. Nonmusician listeners acquire implicit knowledge about these musical structures by mere exposure to music obeying these rules (Bigand, Tillmann, & Poulin-Charronnat, 2006; Tillmann, Bharucha, & Bigand, 2000). This knowledge allows listeners to perceive tonal relationships between tones (Bharucha & Krumhansl, 1983; Krumhansl & Shepard, 1979) and to develop musical expectations for future events, which influence tone perception (Bharucha & Krumhansl, 1983; Bigand & Pineau, 1997; Tillmann, Janata, Birk, & Bharucha, 2003). To test for the influence of tonal knowledge on memory for single tones, Krumhansl (1979) used a delayed recognition task. Standard and comparison tones were separated by an intervening tonal or atonal sequence. Participants showed more stable memory representations of tones that belonged to the tonality instilled by the interfering tonal sequence – a result indicating that musical regularities influence mental representations of tones. This finding has been extended to the observation that participants show better memory performance for tonal compared to atonal chord sequences and melodies (Bharucha & Krumhansl, 1983; Dowling, 1991). Furthermore, Schulze, Mueller, and Koelsch (2011) reported that musicians, but not nonmusicians, showed better WM performance for tonal compared to atonal sequences. This was reflected in a stronger activation of a lateral (pre-)frontal–parietal network during a WM task for tonal compared to atonal sequences. A similar network has been previously reported to underlie WM performance, which was improved by stimulus-inherent structure for auditory-verbal and visual stimuli (Bor et al., 2004; Bor et al., 2003; Bor & Owen, 2007).

In the present study, tonal and atonal sequences were used to investigate whether musical structure influences WM performance during a forward (Experiment 1a) and backward (Experiment 1b) recognition task for tone sequences of different lengths in nonmusicians. Participants listened to pairs of tone sequences and indicated whether two sequences were the same or different, with "same" being defined as all tones played correctly in either the same order (forward task) or backward order (backward task). Encoding and maintenance processes were involved in both forward and backward tasks, and while maintenance was sufficient for the forward task, manipulation (i.e., reordering of the elements of the sequence) was required for the backward task.

For the forward task, based on previous findings (Bharucha & Krumhansl, 1983; Dowling, 1991), we expected better WM performance for tonal sequences than for atonal sequences. For the backward task, two alternative hypotheses could be made for the influence of tonal structure on WM performance: Tonal structure might increase WM performance also in the backward task (as for the forward task) or the benefit of tonal structure on WM performance might decrease or vanish (benchmark effects of WM have been observed during forward recall, but were less pronounced or absent during backward recall, as observed for words presented visually, Bireta et al., 2010; and auditorily, Hulme et al., 1997).

Experiment 1

Experiment 1 investigated whether nonmusicians – who have implicit tonal knowledge (Bigand & Poulin-Charronnat, 2006) – can use musical structures (tonal, atonal) to improve WM performance for tone sequences during a forward (Experiment 1a) and backward (Experiment 1b) recognition task.

Experiment 1a (Forward Recognition Paradigm)

METHOD

Participants. Twenty students from the University of Lyon participated in Experiment 1a. The mean age was 20.00 years (*SD* = 2.85 years; age range: 18 to 28). Nonmusicians received on average 2.25 years (*SD* = 3.43 and a median of 0) of music training, as measured by years of musical instruction for an instrument. Twelve of these participants had not received any musical instruction (0 years).

Material. Half of the tone sequences were tonally structured. All tones belonged to one tonality (C major) and their progression respected musical structures as defined by the Western tonal system. In particular, most of the tonal sequences ended on the tonic pitch (C), and some ended on the dominant pitch (G). Two of the seven-tone tonal sequences ended on D (see below for the description of different sequence lengths).

The other half of the sequences were atonal: The tones did not belong to a single tonality and did not have an obvious tonal structure, but were generated using a "scale" that made tonal interpretation difficult or impossible. The tonally structured sequences and the atonal sequences were matched for various parameters: melodic contour, frequency of occurrence of the tones, range between highest and lowest tones. Table 1 (see Appendix) presents some examples of the tonal and atonal sequences we used. Sequences, consisting of 5, 6, or 7 tones, were presented in pairs, and the sequences of a pair could be either the same or different. For the different pairs, two nonadjacent tones were exchanged so that the melodic contour was preserved (e.g., C A F E G – C A G E F). The first tone of the second sequence was never changed.

Tonally structured sequences were created by using a set of six tones from the C major scale in equal temperament: C4 (262 Hz), D4, E4, F4, G4, A4 (440 Hz). Atonal sequences were created by using another set of six tones: C#4 (277 Hz), E4, F#4, G4, G#4, B4 (494 Hz) in a pseudo-scale structure so that a tonal interpretation in a particular key would be relatively difficult for the shorter sequences and impossible for the longer sequences.

We used the key-finding algorithm proposed by Krumhansl and Schmuckler (cited in Krumhansl, 1990) to analyze the strength of tonal centers established by the melodic contexts. All tones of the five-, six-, and seven-item sequences (tonal and atonal) were correlated with the tone profiles of the 12 major and 12 minor keys, respectively (these tone profiles resulted from subjective judgments of listeners on how well a probe tone fits with a preceding tonal context; Krumhansl & Kessler, 1982). The maximum positive correlation provides an indication of the most strongly established key, and the maximum negative correlation indicates the least likely key. For our material, the maximum correlation for tonal sequences in all conditions was, as expected, with the C major key: five-item sequences: $r(10) = .85$; six-item sequences: $r(10) = .83$; seven-item sequences: $r(10) = .85$; all correlations were significant with $p < .001$. These correlations did not differ significantly from each other ($p > .43$), suggesting that the installed tonality did not differ between the sequences of different length. Correlations for atonal sequences with the C major key were all inferior to .18, and did not differ significantly from each other ($p > .34$).

For both tonal and atonal sequences, each tone had a duration of 500 ms. In the sequences, tones were presented with an interstimulus interval of 20 ms, resulting in a stimulus-onset asynchrony of 520 ms.

APPARATUS

The stimuli were created with the software Cubase 5.1 (Steinberg) and a Halion Sampler (Steinberg) using either cello (50% of the trials) or trumpet timbres (50 % of the trials). The software Presentation (Neurobehavioural Systems) was used to present the stimuli and to record participants' responses.

PROCEDURE

Participants listened to pairs of tone sequences. A first sequence (e.g., F G D E C) was presented and after 3 s of silence, a second sequence was presented with all tones being either in the same order (e.g., F G D E C) or not (e.g., F G C E D). Participants were instructed to compare the two sequences and to press one of two mouse buttons to indicate whether the two sequences were the same or different (with "same" being defined as all tones played correctly in the same order). They pressed the space bar to continue with the next trial. At the beginning of the experiment, the task was explained with two same trials and two different trials using five-tone sequences. Error feedback was given only for these practice trials, and it was made sure that participants understood the task. The experiment lasted approximately 45 min.

DESIGN

The experiment consisted of 192 trials: 32 pairs for each length (5/6/7) and each type of material (tonal/atonal), with half of the trials being different and half being the same. A pseudorandomized presentation was used so that: (1) the same tone sequence was not presented consecutively as a same and a different pair, and (2) the type of pair (same/different) changed after at most 3 trials (i.e., no more than three consecutive "same" or "different" trials). The experiment was structured into 4 experimental blocks of 48 pairs each. The first two blocks always started with five-tone sequences (16 pairs), followed by six-tone sequences (16 pairs), and seven-tone sequences (16 pairs). The third and fourth block started with either seven-tone sequences, followed by six-tone, and five-tone sequences, or with five-tone sequences, followed by six-tone and then seven-tone sequences. Two of the blocks were played with a cello timbre, and two with a trumpet timbre, with timbres alternating between blocks. Over participants, eight different block orders were used (differing in the order of presentation of pairs, timbres, and whether the third and fourth block started with short or long sequences).

RESULTS

Performance was analyzed using the signal detection theory by calculating for each participant and for each condition discrimination sensitivity with *d'* (Figure1) and response bias *c* (Figure 2)[1]. For each participant, these analyses were based on Hit rate (i.e., number of correct responses for different trials/number of different trials) and false alarm rate (i.e., number of incorrect responses for same trials/number of same trials). Positive values for *c* arose when the miss rate (incorrect

[1]The correction of *d'* and *c* measures used .01 for cases without false alarms and .99 for the maximum number of hits.

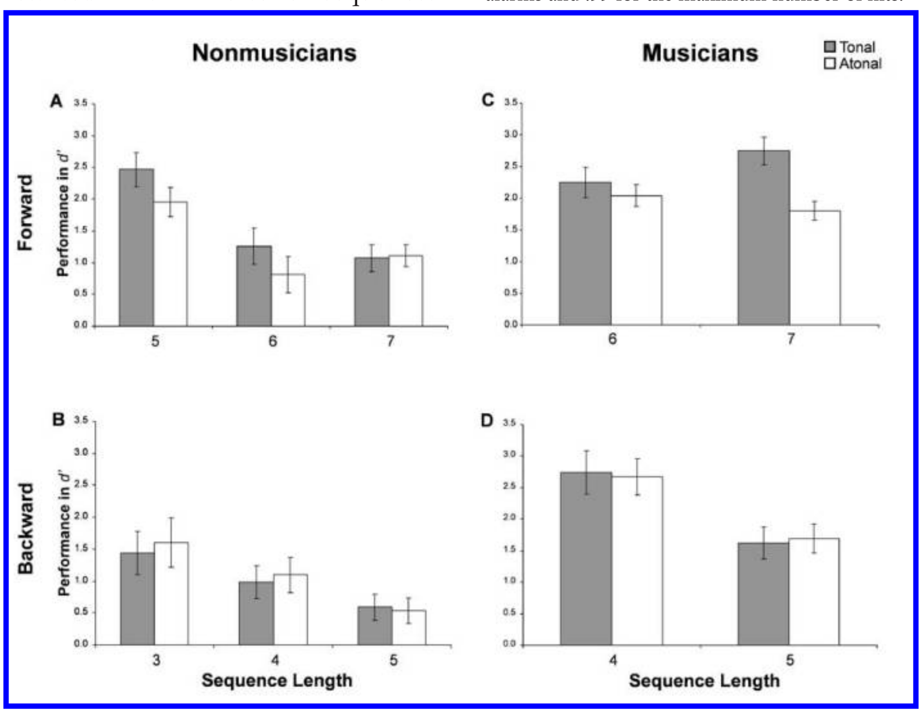

FIGURE 1. WM performance in *d'* (error bars indicating the standard error of mean; *SEM*) as a function of sequence type (tonal/atonal) and sequence length for (A) Experiment 1a: nonmusicians/forward task; 5/6/7 tones, (B) Experiment 1b: nonmusicians/backward task; 3/4/5 tones, (C) Experiment 2: musicians/forward task; 6/7 tones and (D) Experiment 2: musicians/backward task; 4/5 tones.

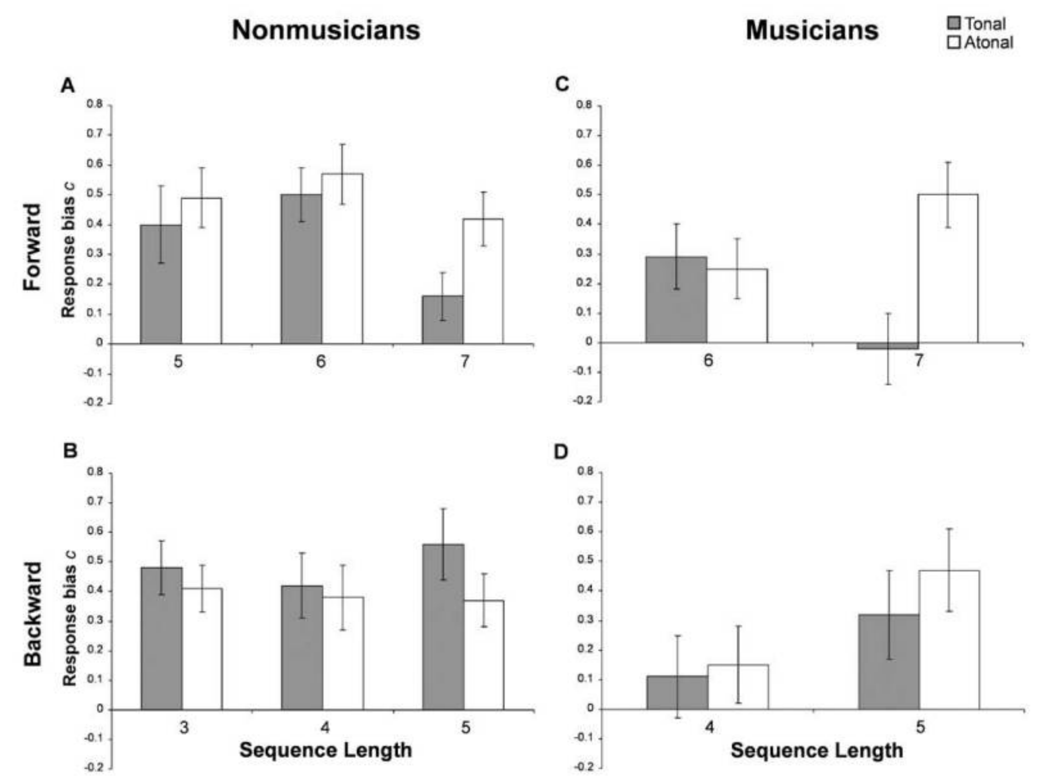

FIGURE 2. Response bias c (error bars indicating the standard error of mean, *SEM*) as a function of sequence type (tonal/atonal) and sequence length for (A) Experiment 1a: nonmusicians/forward task; 5/6/7 tones, (B) Experiment 1b: nonmusicians/backward task; 3/4/5 tones, (C) Experiment 2: musicians/forward task; 6/7 tones and (D) Experiment 2: musicians/backward task; 4/5 tones. Positive values indicate a tendency to answer "same," negative values indicate a tendency to answer "different" and no response bias is suggested by c values around 0.

responses for different trials) exceeded the false alarm rate (incorrect responses for same trials). Positive values indicate a tendency to answer "same," negative values indicate a tendency to answer "different" and no response bias is suggested by *c*-values around 0. Response sensitivity *d'* and bias *c* were analysed using two 2 x 3 ANOVAs with Material (tonal/atonal) and Length (5/6/7) as within-participant factors[2].

Sensitivity d'. (Figure 1) The main effect of Length was significant, $F(2, 18) = 33.78$, $p < .0001$, $MSE = 0.52$, with a better performance for five-tone sequences than for six-tone sequences, $t(19) = 7.52$, $p < .0001$, and seven-tone sequences, $t(19) = 6.40$, $p < .0001$. The main effect of Material was significant, $F(1, 19) = 9.05$, $p = .007$, $MSE = 0.31$, as was the interaction between Length and Material, $F(2, 18) = 3.83$, $p = .03$; $MSE = 0.24$. There was a performance advantage for tonal sequences over atonal sequences, for five-tone sequences, $t(19) = 2.88$, $p = .01$, and six-tone sequences, $t(19) = 3.04$, $p = .007$, but not for seven-tone sequences, $t(19) < 1.00$, $p = .81$. WM performance did not differ between sequences played by a cello timbre or a trumpet timbre, cello: $d' = 1.30$; trumpet: $d' = 1.30$; $p = .99$.

Bias c. (Figure 2) The main effect of Length was significant, $F(2, 18) = 5.70$, $p = .007$, $MSE = 0.11$, with a decreased positive response bias (i.e., decreased tendency to answer "same") for seven-tone sequences compared to six-tone sequences, $t(19) = 3.50$, $p = .002$, while no significant differences in response bias were observed between the five- and the six-, $t(19) = 1.25$, $p = .23$, or seven-tone sequences, $t(19) = 2.03$, $p = .057$. The effect of Material was significant, $F(1, 19) = 5.33$, $p = .03$, $MSE = 0.11$, indicating that participants' positive response bias (i.e., decreased tendency to answer "same") was decreased for tonal sequences compared to atonal sequences. The mean values of *c* (Figure 2) suggest that the tonal-atonal difference was stronger for seven-tone sequences, but the interaction between Material and Length was not significant, $F(2,18) = 1.21$, $p = .31$.

[2]As a Shapiro-Wilk test suggested that performance data (*d'* for tonal and atonal sequences) were not completely normally distributed, non-parametric tests were performed (Friedman test and Wilcoxon test); they confirmed the main effects of the ANOVA and the contrast analyses.

Experiment 1b (Backward Recognition Paradigm)

METHOD

Participants. Twenty students from the University of Lyon took part, none of whom had participated in Experiment 1a. The mean age was 19.63 years (*SD* = 1.74 years; age range: 18 to 24). Nonmusicians received on average 4.32 years (*SD* = 4.30 and a median of 3) of music training, as measured by years of musical instruction for an instrument. Four of these participants had not received any musical instruction (0 years).

Material and Apparatus. Sequences consisted of 3, 4 or 5 tones[3] (examples of the used tonal and atonal sequences are presented in Table 1, Appendix). For "different" trials, the changed tones introduced a contour change in all sequences (e.g., E F C and C E F). It was not possible to preserve the contour for the different sequences because of the short sequences (i.e., the three-tone sequences) and the constraint to keep the first tone unchanged. Note that it has previously been shown that contour changes lead to better memory performance than contour preservation in a forward recognition task (Dowling & Fujitani, 1971). Besides this, material and apparatus were as described for Experiment 1a. We used the key-finding algorithm proposed by Krumhansl and Schmuckler (cited in Krumhansl, 1990) to analyze the strength of tonal centers established by the melodic contexts. All tones of the three-, four-, and five-item (tonal and atonal) sequences were correlated with the tone profiles of the 12 major and 12 minor keys, respectively. As with the forward sequences, the maximum correlation for tonal sequences in all conditions was, as expected, with the C major key: three-item sequences: $r(10) = .91$; four-item sequences: $r(10) = .83$; five-item sequences: $r(10) = .85$; all correlations were significant with $p < .001$. These correlations did not differ significantly from each other ($p > .18$), suggesting that the installed tonality did not differ between the sequences of different length. Correlations for atonal sequences with the C major key were all inferior to .18, and did not differ significantly from each other ($p > .52$). When comparing the correlations between forward and backward sequences, no significant differences, neither for tonal ($p > .18$) nor atonal sets ($p > .34$), were observed. These findings suggest that the installed tonality did not differ between the sequences of different length or between the forward and the backward task.

[3]In a pilot experiment, we observed that participants showed decreased performance during the backward task compared to the forward task. To account for this and avoid a floor effect in performance, we presented participants with shorter sequences in the backward task.

Procedure. Participants listened to pairs of tone sequences. A first sequence (e.g., E F C) was presented, followed by 3 s of silence, then a second sequence. Participants were informed that the tones of the second sequence were played in reversed order – and that they were required to judge whether the second sequence was played backward either in the correct order (e.g., C F E) or in a different order (e.g., C E F). Otherwise, the procedure was as described for Experiment 1a.

Design. The experiment consisted of 192 trials: 32 pairs for each Length (3/4/5) and each Material (tonal/atonal), with half of them being different and half being the same. The pseudorandomized presentation and the presentation of the experimental items in four blocks were as described in Experiment 1a (adapted to the three sequence lengths used here).

RESULTS

One participant, who had answered "same" throughout the entire experiment, was excluded from the analysis. As with Experiment 1a, the response sensitivity *d'* (Figure 1) and bias *c* (Figure 2) were analyzed using two 2 x 3 ANOVAs with Material (tonal/atonal) and Length (3/4/5) as within-participant factors[4].

Sensitivity d'. (Figure 1) The main effect of Length was significant, $F(2, 17) = 8.62$, $p = .001$, $MSE = 1.01$. Participants tended to show better performance for three-tone sequences than for four-tone sequences, $t(18) = 2.10$, $p = .05$, and significantly better performance for three-, $t(18) = 3.44$, $p = .003$, and four-tone sequences, $t(18) = 2.81$, $p = .01$, compared to five-tone sequences. The main effect of Material, $F(1,18) < 1$, $p = .62$, and its interaction with Length, $F(2,17) < 1.00$, $ps > .78$, were not significant. Note that *d'* was significantly above 0 in all conditions ($ps < .01$). As with the forward task, WM performance did not differ between sequences played by a cello timbre or a trumpet timbre: cello: $d' = .79$; trumpet: $d' = 1.02$; $p = .11$.

Bias c. (Figure 2) No significant effects were observed ($ps > .13$).

DISCUSSION

Experiment 1 investigated the effect of tonal structure and sequence length on WM performance. More specifically, we tested whether nonmusicians' implicit knowledge about tonal structure could improve WM performance for tone sequences during a forward (Experiment 1a) and backward (Experiment 1b)

[4]As a Shapiro-Wilk test suggested that performance data (*d'* for tonal and atonal sequences) and response bias *c* were not completely normally distributed, nonparametric tests were performed (Friedman test and Wilcoxon test); they confirmed the main effects of the ANOVA and contrast analyses.

recognition task. Participants performed significantly above chance for both tasks, indicating that nonmusicians were able to manipulate tones in WM. This finding extends previous results of Dowling (1972) from atonal sequences to tonal sequences.

Experiment 1 used the two tasks with three sequence lengths. For both forward and backward tasks, the data confirmed the hypothesis that WM performance (based on maintenance or manipulation) decreased with increasing length of the sequences.

The main finding of Experiment 1a was that musical structure improved WM performance during a forward recognition task of tone sequences in nonmusicians: WM performance differed for structured (tonal) compared to unstructured (atonal) sequences, which was reflected in the sensitivity measure *d'* and in the response bias *c*. As suggested by the *d'* data, the tonal structure helped participants to improve encoding and/or maintaining of pitch information, in particular for the five- and six-tone sequences. The *c* data revealed that participants overall showed a response bias towards answering "same" (i.e., the miss rate exceeded the false alarm rate), but that this response bias was decreased for tonal sequences in comparison to atonal sequences. For the seven-tone sequences, the processing advantage for the tonal sequences was reflected in a considerably decreased response bias, which approached 0 (i.e., bias-free responses), even though the tonal processing advantage was not shown in *d'*, which was rather low overall.

As participants were mostly nonmusicians, the findings (sensitivity *d'*, bias *c*) indicate that implicit tonal knowledge (Bigand & Poulin-Charronnat, 2006) allows listeners to benefit from the musical structure of the tone sequences during an auditory forward recognition task. This extends previous findings in other domains that have shown that structure in verbal and spatial material can increase WM performance of these materials (Bor et al., 2004; Bor et al., 2003; Savage et al., 2001). For the forward task, which required maintenance of tone information, participants had fewer difficulties maintaining the tonal sequences in WM compared to the atonal sequences. This finding is in agreement with previous results obtained using a recognition paradigm for chord sequences (Bharucha & Krumhansl, 1983) and transposed melodies (Dowling, 1991).

In contrast to the forward task, no effect of tonal structure on WM performance was observed during the backward task (Experiment 1b) for response sensitivity *d'* or response bias *c*. This difference in the effect of tonal structure can be interpreted in the framework of previous findings on verbal material showing that typical and rather robust effects of forward recall are not observed during backward recall (Bireta et al., 2010; Hulme et al., 1997), indicating that WM processes are different during forward and backward tasks. An alternative explanation is that tonality is structured in time. The backward task requires participants to manipulate and recognize the test sequence against this time-directed structure and, as a consequence, the presence of tonality might not have presented a processing advantage for WM.

However, the fact that nonmusicians did not show better performance for tonal compared to atonal sequences in the backward task might be related to their weaker performance level (even though performance was above chance level) in comparison to the forward task. This might also explain the lack of tonality effect for the seven-tone sequences in the forward task. Furthermore, it has been suggested that tonal structure might increase auditory WM performance for musicians, but not (or less) for nonmusicians (Schulze, Mueller, & Koelsch, 2011). Therefore, for Experiment 2, we recruited musicians, experts in the music domain who should reach overall higher performance levels.

Experiment 2

Because of the alternative hypothesis linked to nonmusicians' weaker performance levels, Experiment 2 investigated WM for tonal and atonal sequences in musicians. Previous memory research has shown that experts (e.g., chess experts) are particularly able to use structure to improve memory performance (for an overview of theories on expert memory, see Gobet, 1998; Gobet et al., 2001). For example, Ericsson and Kintsch (1995) suggested that experts' specific knowledge stored in long-term memory is quickly accessible for WM processes, giving experts an advantage over nonexperts in tasks related to their domain of expertise. For tones, it has been reported that musicians can benefit from musical structure during recall (using musical notation) of auditorily presented tone sequences (Deutsch, 1980), and for visually presented melodies (Halpern & Bower, 1982). Boltz and Jones (1986) reported a similar finding for musicians with material respecting a predefined rule (e.g., recursive hierarchical): Three-tone sequences were better recalled when the three tones respected the rules than when these were chained without regularities.

For our forward and backward recognition tasks, we expected that musicians reach overall higher WM performance levels than nonmusicians. If it is the nonmusicians' weak performance level in Experiment 1 that prevented us from observing a benefit of musical structure during the backward recognition task, then we should observe an advantage of tonal sequences over atonal sequences in musicians also for the backward task. However, if tonal structure does not improve WM performance during manipulation of tone information, performance during the backward task should not differ between tonal and atonal sequences even for musicians, despite their overall better performance. In Experiment 2, musicians were tested in both forward and backward tasks in one experimental session, and thus only two of the three sequence lengths in each of the experimental tasks were used (see Method).

METHOD

Participants. Twenty musicians were recruited from a local orchestra and from the French National Music Conservatory in Lyon to take part in Experiment 2. The mean age was 25.35 years (SD = 6.32 years; age range: 19 and 42). The age when participants started to play their first instrument ranged from 4 to 12, with a mean of 7.55 (SD = 1.90) and a median of 8. Musicians received on average 17.65 years (SD = 6.12, median of 16) of music training, as measured by years of musical instruction for an instrument. Years of music training (years of musical instructions) of musicians in Experiment 2 differed significantly from the musical background of the nonmusicians in Experiment 1a ($p < .0001$) and Experiment 1b ($p < .0001$).

Materials and apparatus. The same stimuli (except for the shortest sequences in forward and backward tasks) and apparatus as in Experiment 1 were used.

Procedure. In order to test musicians with both forward and backward tasks in the same experimental session, Experiment 2 was a shortened version of Experiments 1a and 1b: For the forward task, six- and seven-tone sequences, and for the backward task, four- and five-tone sequences were presented. Each task had a duration of 30 min, and the two tasks were separated by a break of 30 min. The order of tasks was counterbalanced across participants. Otherwise, the procedure was as described for Experiment 1.

Design. Each task consisted of 128 trials: 32 pairs for each Length (6/7 or 4/5) and each Material (tonal/atonal), with half of them being different and half being the same. The pseudorandomized presentation and the presentation of experimental items in four blocks were as described in Experiment 1 (adapted to the two sequence lengths used here).

RESULTS

As described in Experiment 1a, response sensitivity d' and bias c were calculated for both forward and backward tasks and then respectively analyzed using two 2 x 2 ANOVAs with Material and Length as within-participant factors[5].

Forward task - Sensitivity d'. (Figure 1) No effect of Length was observed, $F(1, 19) < 1.00$, $p = .42$, but a significant effect of Material, $F(1, 19) = 9.75$, $p = .006$, $MSE = 0.69$, and a significant interaction between Material and Length, $F(1, 19) = 6.00$, $p = .02$, $MSE = 0.44$, were found. The performance difference between tonal and atonal sequences (i.e., with better performance for the tonal sequences) was more pronounced for seven-tone sequences, $t(19) = 4.25$, $p < .0001$, than for six-tone sequences, $t(19) < 1.00$, $p = .40$. In addition, performance was better for seven- than for six-tone sequences, $t(19) = 2.32$, $p = .03$, if the sequences were tonal, while performance decreased with length if they were atonal, even if not significantly, $t(19) = 1.10$, $p = .29$. As with nonmusicians, WM performance did not differ between sequences played by a cello timbre or a trumpet timbre: cello: $d' = 2.11$; trumpet: $d' = 1.94$; $p = .26$.

Forward task - Bias c. (Figure 2) No significant effect of Length, $F(1, 19) < 1.00$, $p = .60$, but a significant effect of Material, $F(1, 19) = 22.63$, $p < .0001$, $MSE = 0.05$, and a significant interaction between Length and Material, $F(1, 19) = 12.15$, $p = .002$, $MSE = 0.13$, were observed. Response bias differed significantly between tonal and atonal for the seven-tone sequences, $t(19) = 5.50$, $p < .0001$, but not for the six-tone sequences, $t(19) < 1.00$, $p = .71$.

Backward task - Sensitivity d'. (Figure 1) A significant main effect of Length, $F(1, 19) = 35.03$, $p < .0001$, $MSE = 0.63$, was observed, with better performance for four-tone sequences than for five-tone sequences, $t(19) = 5.92$, $p < .0001$. The main effect of Material, $F(1, 19) < 1$, $p > .99$, and its interaction with Length, $F(1, 19) < 1.00$, $p = .63$, were not significant, indicating that musicians' performance in the backward task was dependent on length, but not on tonal structure. As with nonmusicians, WM performance did not differ between sequences played by a cello timbre or a trumpet timbre: cello: $d' = 1.99$; trumpet: $d' = 1.99$; $p = .81$.

Backward task - Bias c. (Figure 2) We observed a significant effect of Length, $F(1, 19) = 12.56$, $p = .002$, $MSE = 0.11$, but no significant effect of Material, $F(1, 19) = 3.1$, $p = .10$, and no interaction between Length and Material, $F(1, 19) < 1.00$, $p = .55$.

[5]As a Shapiro-Wilk test suggested that performance data (d' for tonal and atonal sequences) and response bias c were not completely normally distributed, nonparametric tests were performed (Wilcoxon test); they confirmed the main effects of the ANOVA and the contrast analyses.

DISCUSSION

Musicians performed better for tonal sequences than for atonal sequences in the forward task, but not in the backward task. This result mirrored nonmusicians' data (Experiment 1)[6].

For the backward task, the finding that musicians reached higher performance levels than did nonmusicians, but still did not show a tonal structure effect, suggests that the absence of a tonal structure effect for nonmusicians cannot be attributed to nonmusicians' low performance level. As discussed above, this finding might thus suggest the missing advantage of the time-directed tonal structures when required to reverse those in time, or, alternatively, that forward and backward recognition tasks rely on different underlying memory processes, as previously indicated for recall of word lists (Bireta et al., 2010; Hulme et al., 1997).

In the forward task, musicians showed a tonal structure effect for both *d'* and *c*. As with nonmusicians (Experiment 1a), musicians' performance was not influenced by response bias (i.e., *c* was close to 0, suggesting no response bias) for tonal sequences with seven tones.

While performance of nonmusicians for these longer sequences was low overall ($d' = 1.09$), the advantage of tonal structure was also reflected in the *d'* for the musician participants: Performance of the seven-tone tonal sequences was better than that of their atonal counterpart. Performance of the seven-tone tonal sequences was even better than for the shorter tonal sequences, thus showing a reversed length effect. Musicians' memory thus seemed to benefit most particularly from the tonal context of the longer sequences. In contrast, for the atonal sequences, this help of tonal structure did not apply, and musicians seemed to be limited by more general memory span restrictions for atonal sequences, leading to a slightly decreased performance for the longest sequences.

In summary, our findings suggest that during the forward task (maintenance), but not during the backward task (manipulation), musicians use their knowledge about musical structure to process the tone sequences and keep that information more efficiently in memory.

General Discussion

The main aim of our study was to investigate the potential influence of tonal structure on WM for tones using forward and backward recognition tasks. Because of the relatively low (though above chance) performance levels of nonmusician participants in some conditions of Experiment 1, we tested musician participants with both tasks in Experiment 2.

In the forward task, nonmusicians and musicians showed better performance (as measured by sensitivity *d'*) for tonal compared to atonal sequences. This was accompanied by a decreased response bias (approaching 0 or at least a decreased tendency to answer same) for tonal sequences, compared to atonal sequences. These results indicated that it was more difficult for participants to maintain/rehearse the atonal sequences in WM.

This data set supports the general hypothesis that structure in materials can increase WM performance (Bor et al., 2004; Bor et al., 2003; Savage et al., 2001; Tulving, 1962), and the more specific hypothesis that musically structured material can increase WM performance during maintenance of tone sequences (Bharucha & Krumhansl, 1983; Krumhansl, 1979). The finding that nonmusicians benefit from tonal structures indicates that implicit musical knowledge (Bigand & Poulin-Charronnat, 2006) is sufficient to support WM for tone sequences. In contrast to a previous study (Schulze, Mueller, & Koelsch, 2011) that reported beneficial effects of tonality for musicians but not for nonmusicians (although nonmusicians showed a trend in the same direction), our study observed better WM performance for tonal sequences for both musicians and nonmusicians. This could be due to (1) a stronger installed tonality in the present material (e.g., all tonal sequences were based on one key: C major, while Schulze, Mueller, & Koelsch (2011) used different keys over the experimental set of sequences), and (2) better overall performance of nonmusicians in the present study, while nonmusicians performed at chance level in the atonal condition in the previous study (Schulze, Mueller, & Koelsch, 2011)[7].

But how could the tonal structure improve WM for tones? Dowling (1991) manipulated systematically the

[6]Response sensitivity *d'* was analyzed using two 2 x 2 ANOVAs with Material (tonal/atonal) and Length (6/7 or 4/5) as within-participant factors and Group (musicians/nonmusicians) as between-participant factors for forward and backward tasks, respectively. For both tasks, a significant main effect of Group was observed ($p < .001$), with better performance for musicians than nonmusicians. In addition, for the forward task, the interaction between Material, Length, and Group was significant ($p = .001$), which confirmed the discussed difference: For nonmusicians, the tonal advantage was observed for six-tone sequences rather than seven-tone sequences, while the reverse was observed for the musicians. For the backward task, only the interaction between Length and Group was significant ($p = .023$): Whereas both musicians and nonmusicians showed better performance for four-tone sequences than for five-tone sequences, the performance difference between these two lengths (*d'* for four-tones minus *d'* for five-tones) was more pronounced ($p = .013$) in musicians ($d' = 1.10$) compared to nonmusicians ($d' = 0.46$).

[7]Note that the WM task differed between both experiments: Schulze, Mueller, and Koelsch (2011) presented five-tone sequences followed by a probe tone after a delay of 4 - 6 s and participants had to indicate whether this tone had been presented in the sequence.

tonal strength of melodies; that is, how strongly the tonal framework was established by the used tones. In a continuous running memory paradigm, memory for exact intervals was observed only for strong tonal melodies. Dowling (1991) suggested that interval, contour, and tonality are not encoded independently, but rather form an integrated whole. This might lead to a stronger memory trace for tonal melodies over atonal melodies (as observed in our present study), with atonal melodies missing the potential integration in a tonal framework (see also Cuddy & Lyons, 1981).

An alternative explanation is that listeners' knowledge about tonality might help to memorize and structure this information; for example, by decreasing the amount of information to be memorized. Chunking allows perceivers to reorganize information into familiar and regular structures (Gobet et al., 2001; Miller, 1956), notably with the help of perceivers' knowledge about possible structures stored in long-term memory (Cowan, 2000; Ericsson & Kintsch, 1995). In the present study, tonal and atonal sequences were based on a set of six tones, but only for the tonal sequences, these tones all belonged to one tonality. Therefore, listeners' knowledge about tonalities and tonal structure might have improved WM performance for the tonal sequences. Future studies need to investigate more specifically how tonal material might be chunked by listeners to increase WM capacities (e.g., by exploiting implicit harmony).

The lack of a tonality effect for six-item sequences in musicians is surprising given that we observed (1) an effect of tonality with the same six-item material in nonmusicians and (2) an effect of tonality for the seven-item sequences in musicians. As indicated by the results of the key-finding algorithm proposed by Krumhansl and Schmuckler (cited in Krumhansl, 1990), this result of musicians cannot be explained by differences in the degree of tonal structure. It might be that for musicians, performance was overall rather good for the six-item sequences and that the advantage for the tonal sequences only influenced performance for the longer, more difficult seven-item sequences. Although we have no further explanation for this observed effect at this point, it would be interesting to compare musicians' WM performance for tonal and atonal sequences for shorter and longer sequences (e.g., four-item sequences to eight-item sequences) than in the present experiment aiming to confirm this pattern.

In contrast to the forward task, neither nonmusicians nor musicians showed better performance for tonal than for atonal sequences in the backward task. There were no differences in the correlations indicating the installed tonality between the sequences used for different lengths in the backward task and those in the forward task (as calculated with the key-finding algorithm proposed by Krumhansl and Schmuckler; cited in Krumhansl, 1990). Therefore, a difference in the degree of tonal structure cannot account for the observed differences in performance (e.g., no difference between tonal and atonal sequences for the backward task).

The fact that musicians reached higher performance levels and did not show a tonal structure effect suggests that the absence of a tonal structure effect for nonmusicians cannot be attributed to their lower performance levels. In addition, the lack of tonal structure effect cannot be explained as a consequence of the shortness of all used sequences (i.e., differing in the clarity of the instilled tonal structure) because five-tone sequences showed the tonal advantage in the forward task, but not in the backward task.

These findings thus suggest that even with explicit musical knowledge, listeners show an advantage of tonal sequences only for forward recognition (maintenance), but not for the backward recognition (manipulation) of tone information. This might be a consequence of the nature of auditory stimuli, and particularly of tonal structures. Musical information unfolds over time in a structured, directional way. Backward recognition requires the reversal of this structure, thus removing the processing advantage that tonality provides in the original forward order. An alternative explanation is based on previous studies investigating memory for verbal material that have suggested different mechanisms underlying forward and backward recall. For example, the following effects that have been well established during forward recall (Baddeley, 2003) were absent or highly attenuated during backward recall: the word length effect (Bireta et al., 2010; Tehan & Mills, 2007), the irrelevant speech effect (Bireta et al., 2010), the phonological similarity effect (Bireta et al., 2010; Tehan & Mills, 2007), and the concurrent articulation effect (Bireta et al., 2010). Therefore, different mechanisms underlying forward and backward WM could explain why tonal structure improved WM performance only during the forward task.

Furthermore, the degree of required manipulation might potentially influence the beneficial effect of tonality on WM for tones. Schulze, Mueller, and Koelsch (2011) presented a sequence of five tones that was followed by one test tone after a short silent interval. Participants had to indicate whether the test tone had been presented during the sequence. This task required segmenting the tone sequence and selecting partial information, because participants had to compare the test tone with every tone of the sequence. However, the task did not require a complete inversion of the sequence as did the backward task in the present study. Thus, the task of Schulze, Mueller, and Koelsch (2011) might have required more manipulation than the forward task (because one tone had to be selected and monitored in forward sequences), but less manipulation than the backward task of our study (not the entire sequence needed to be re-ordered and, most importantly, temporal relations between the tones were preserved). Schulze, Mueller et al. (2011) reported a beneficial effect of tonality for musicians, and only a nonsignificant tendency towards a better performance for the tonal compared to the atonal sequences for the nonmusicians. In the present study we observed a beneficial effect of tonality for our forward task, but not our backward task (which required a rather strong manipulation of the sequence, namely complete inversion) for nonmusicians and musicians. This suggests that the beneficial effect of musical structure on WM manipulation might depend on the degree of manipulation required for the task or on the type of manipulation (with a cost for complete reversal acting against the musical structure).

While our results on melody recognition showed different effects of musical structure on forward and backward recognition (thus maintenance and manipulation of tone information in WM), future studies need to further investigate the underlying mechanisms, such as the influence of increased attention demands in the backward task because of structure reversing versus the involvement of different memory representations (see Ashman & Das, 1980; Li & Lewandowsky, 1995; Rosen & Engle, 1997, for a discussion of these two approaches explaining performance difference between forward and backward recall of word lists).

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APPENDIX
TABLE 1. Examples of Auditory Sequences

	Sequences	Structure	Sequence example
Forward task (*n* = 192)	five-tone (*n* = 64)	tonal (*n* = 32)	F G D E C – F G D E C
			F G D E C – F G **C** E **D**
		atonal (*n* = 32)	F# G# E G C# – F# G# E G C#
			F# G# E G C# – F# G# **C#** G **E**
	six-tone (*n* =64)	tonal (*n* = 32)	E F A D G C – E F A D G C
			E F A D G C – E **G** A D **F** C
		atonal (*n* = 32)	F# G# B E G C# – F# G# B E G C#
			F# G# B E G C# – F# **G** B E **G#** C#
	seven-tone (*n* = 64)	tonal (*n* = 32)	G A D E F G C – G A D E F G C
			G A D E F G C – G A **C** E F G **D**
		atonal (*n* = 32)	F F# C C# E F B – F F# C C# E F B
			F F# C C# E F B – F F# **B** C# E F **C**
Backward Task (*n* = 192)	three-tone (*n* = 64)	tonal (*n* = 32)	E, F, C – C, F, E
			E, F, C – C, **E**, **F**
		atonal (*n* = 32)	F#, G, C# – C#, G, F#
			F#, G, C# – C#, **F#**, **G**
	four-tone (*n* = 64)	tonal (*n* = 32)	E D G C – C G D E
			E D G C – C **D** **G** E
		atonal (*n* = 32)	F# E G C# – C# G E F#
			F# E G C# – C# **E** **G** F#
	five-tone (*n* = 64)	tonal (*n* = 32)	F G D E C – C E D G F
			F G D E C – C **D** **E** G F
		atonal (*n* = 32)	F# G# E G C# – C# G E G# F#
			F# G# E G C# – C# **E** **G** G# F#

Note: *n* indicates the number of sequences used in Experiment 1.