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Research report

Memory structures for encoding and retrieving a piece of music: an ERP investigation

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Abstract

This study examined behavioral and neural correlates of expert musical memory, specifically the hypothesis that particular bars within a complex piece of music would serve as structural markers for encoding to and retrieval from memory. Six pianists were asked to learn and memorize a set prelude by J.S. Bach for performance, and to identify bars that they employed for structuring the prelude into component sections. Following performance from memory, the participants took part in a visual recognition memory task, in which single bars from the prelude had to be distinguished from matched new bars. During the recognition task, the electroencephalogram (EEG) was recorded, and event-related potentials (ERPs) from correctly identified prelude stimulus trials were averaged according to their hypothesized status into "structural" and "nonstructural" bars. The results showed that correct identification of structural bars was significantly faster (and tended to display higher accuracy) than recognition of non-structural ones. In addition, recognition of structural bars was associated with a significantly greater negative ERP peak of 300–400 ms latency and a right centro-parietal scalp distribution. This mid-latency negativity appears to index processing of stimuli that served as cues for encoding and retrieval of a complex semantic structure, and is qualitatively and conceptually different from other previously identified recognition memory ERPs (such as the "old/new" effect), as well as from the classic N400 ERP. The data support existing theories of expert memory and music cognition.

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Music cognition; Memory; Expertise; Retrieval structures; EEG; ERP

1. Introduction

Listening to an accomplished recital of a great piece of music, performed from memory, constitutes a much-cherished cultural experience, as well as an astounding achievement of recollection by the performing artist. Exceptional memory is a hallmark of expertise, and a number of theories have been proposed to explain how experts—from chess grandmasters to concert pianists—are able to achieve such prodigious feats of memory in performance. Theories that have been proposed to account for expert behavior include Elementary Perceiver and Memorizer (EPAM) [22], Chunking Theory [12,13], Skilled Memory Theory [10,11], Adaptive Control of Thought (ACT*) [1], State, Operator, And Result (SOAR) [36], and Long-Term Working Memory Theory [17], as well as a range of proposals that can be classified roughly into a "knowledge-based" paradigm (e.g. Ref. [30]; see Ref. [27] for a review).

In many respects, Skilled Memory Theory has been accepted as accounting for the remarkable memory abilities observed in experts across several domains [2–4,17,36,44]. The theory is based on three core principles. First, experts

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are able to use their existing knowledge structures in semantic memory to store information during skilled performance of a given task. Second, this information is indexed into a *retrieval structure*, a memory mechanism in which cues are used strategically to facilitate the efficient encoding and retrieval of information in long-term memory (LTM). Third, the time required by encoding and retrieval operations decreases with extended practice. Retrieval structures are central to the theory and were initially proposed to explain how subjects, after considerable training, were able to expand their memory capacity on the digit-span task by over 1000% (see case studies of SF, DD, and RE; [10,11,15,21]). Subsequent studies of mnemonists and memory experts have provided supporting evidence for such acquired mechanisms (see Refs. [16,19,20,35,46]).

Ericsson and Kintsch have recently extended Skilled Memory Theory into the Long-Term Working Memory (LT-WM) Theory [17]. They present compelling evidence from a range of fields (including digit span memory, mental multiplication, mental abacus calculation, chess, medicine, text comprehension, and memory for menu orders) in support of their argument that traditional models of human memory do not account for the greatly expanded working memory capacity of experts and skilled performers. In doing so, they address previously voiced doubts concerning the general involvement of LTM in working memory (see Refs. [3,44]). Of crucial importance to the LT-WM framework is the way in which domain-specific information is stored and accessed. Ericsson and Kintsch propose that information is encoded and retrieved by means of (1) a retrieval structure (as above) and/or (2) through knowledge-based associations connecting items to other items or to LTM patterns and schemas. The task demands on memory dictate which method will be used in order to achieve the most reliable and rapid storage of and access to LT-WM.

Recently, much work has gone into identifying characteristics of the integrated LTM representations that musicians form when memorizing music. Music is a particularly apt domain for testing theories of expert memory because the demands for future retrieval are unusually clear. Within the Western art music tradition, for instance, it is commonplace for musicians to memorize complex musical works for performance. Moreover, the lofty performance standards expected in the world's top concert venues—as well as the availability of high quality recordings and audiences' familiarity with standard pieces in every instrument's repertory—establish exacting demands for recall accuracy.

In a longitudinal investigation, Chaffin et al. [5–9] systematically studied a concert pianist's practice and memorization of the "Presto" from J.S. Bach's *Italian Concerto*. They analysed over 33 h of videotaped practice and found that the pianist started and stopped her practice more frequently at "structural" boundaries (complying with the work's formal structure) than in the middle of sections. From this, they argued that, since the encoding of information was organized according to structural components, the retrieval of that information must too be dependent on the same components. They used comments made by the pianist during and after each practice session and in interviews to confirm their interpretation of the data. In addition, a follow-up study 27 months later (in which she was asked to write out the first page of the score from memory without prior warning) revealed that recall accuracy was significantly better for the bars beginning each section than for bars at other locations. This provided behavioral support for their claim that the music's structure afforded an enduring foundation for the pianist's LTM representation of the piece.

Subsequent work by Williamon et al. [49,50] offers further support for the notion that skilled musicians use their understanding of musical structure as the basis for organizing retrieval cues associated with encoded information. Similar to Chaffin's research, the practice of 22 pianists at different levels of skill was recorded and studied. From the recorded practice, values for the frequency of practice starts and stops on (individually identified) "structural," "difficult," and "other" bars were obtained. The analyses revealed that all pianists, regardless of skill level, started and stopped their practice increasingly on structural bars and decreasingly on difficult bars, from the initial practice session until the session just prior to performance. This pattern of results was most pronounced for musicians at the highest levels of skill and, thereby, suggests that the effective use of highly ordered retrieval schemes for memorizing music develops as a function of expertise.

Still, very little is actually known about the neural substrates of musical memory. This is due to the fact that music retrieval, at the level observed in elite performers, is closely linked to the kinesthetic and movement-oriented aspects of performance, as well as to the performance environment itself [47–50]. However, given that so much behavioral data now confirms the prevalence of musical structure in encoding and retrieval processes of expert musicians (at least within the Western art music tradition), the prospects for carrying out systematic, laboratory-based investigations in this area seem promising (see Refs. [25,26]).

Event-related brain potentials (ERPs), reflecting stimulus- or response-locked averaged electroencephalographic (EEG) activity, have proved to be an important tool for assessing brain activity related to processes of memory encoding and retrieval (see Refs. [24,40] for reviews). For example, ERP studies have shown that brain responses during the encoding of stimuli that subsequently are recalled successfully differ from those that are not remembered [37,43]. With respect to memory retrieval, on the other hand, it is a well-established finding that word stimuli which are correctly classified as "old" (i.e. learned during a pre-testing phase) versus "new" elicit a positive event-related component maximal over left parietal scalp regions, referred to as the "old/new effect" [28,41]. In the current study, we employed the ERP technique in order to disclose possible differences in the processing of musical bars that may be of particular structural importance for the encoding and retrieval of a memorized piece.

We hypothesized that, if there are such structurally crucial bars that aid the encoding and retrieval of a piece of music by providing a cue for the retrieval of a subsequent section of music, then these bars would be processed differently to ordinary bars within the piece. Specifically, recognition of such bars should be accomplished with greater ease, and they should be distinguishable from other bars in terms of the brain activity underlying their retrieval. In order to test these predictions, we devised a recognition memory task that required participants (a group of advanced pianists) to identify bars from a piece of music they had recently learned to play from memory (the Prelude in A Minor from Bach's *Well-Tempered Clavier II*, BWV 889). The pianists were to distinguish bars belonging to the Bach prelude from similar bars not belonging to the prelude. Of interest to our predictions was whether responses to hypothesized "structural" bars would differ, in terms of reaction times and event-related brain potentials, from bars that also belonged to the prelude but were presumed to be "non-structural." Thus, even though structural and non-structural bars belonged to the same response category in the recognition task (prelude versus non-prelude), we expected differing behavioral and cortical responses to these stimuli.

2. Materials and methods

2.1. Participants

The participants were six right-handed piano students (1 male, 5 females; mean age=22.33 years, S.D.=2.34) from the Royal College of Music, London (henceforth RCM), with a mean of 17.33 years of formal training on the piano (S.D.=2.94). The overall standard of playing among these students was high, with each receiving marks of distinction in recent performance recitals at the RCM and engaging in active performing careers outside of the College. They were recommended for participation in the study by their piano professor (who was the same for all participants). Three were third- or fourth-year undergraduate students, and three were postgraduate students specializing in solo performance. At the start of the study, the participants were asked to provide a self-assessment (from 1=poor to 7=excellent) of their abilities to "memorize thoroughly" and "memorize quickly," compared with other pianists at the RCM. Mean ratings on these two aspects of skill were, respectively, 5.33 (S.D.=1.21) and 5.00 (S.D.=1.26), indicating that these students perceived their general ability to memorize music to be at least on a par with (if not better than) other pianists.

2.2. Learning phase

The participants were required to learn, for a memorized performance, the Prelude in A Minor from J. S. Bach's *Well-Tempered Clavier II* (BWV 889). This composition was selected specifically for its well-established position in the standard piano repertoire and for its high degree of difficulty to learn and memorize for performance. None of the participants had played this piece prior to the study, and no restrictions were placed on the amount of time spent practicing or the total number of practice sessions. The performance took place in a performance laboratory at the RCM, with one researcher present.

2.3. Identification of "*structural*" and "*non-structural*" bars

Following each performance, the pianists were interviewed on the practice and memorization process. All interviews were videotaped. One set of interview questions, as per Williamon and Valentine's study, "required that participants indicate whether they had thought of their assigned composition as having component sections during both practice and performance, and if so, why and how they partitioned it" (Ref. [49], p. 13). Responses to these questions were variable and reflected a range of different conceptualizations of the piece, which seems characteristic of the retrieval structures developed by expert musicians [45,50]. In the light of such differences between pianists, a faculty member at the RCM, who was not connected with the study, was asked to provide a formal analysis of the composition. Bars were subsequently classified by the researchers (unbeknownst to the participants) as structural if they were the first bar in sections identified by both the individual pianists and the faculty member (n=8; specifically, bars 1, 6, 10, 14, 17, 21, 25, and 29; although all pianists identified more boundaries than in the formal analysis, these were individual-specific and linked to idiosyncratic views on the technical and musical nature of the piece). All remaining bars were classified as non-structural (n=24). In this way, we were able to arrive at a classification system that both tapped into each individual's understanding of the musical structure and allowed for structural parity across the sample (indeed, no other structural bars were commonly identified by *all* of the participants).

2.4. Recognition memory task

A number of studies within the music psychology and education literature indicate that musicians typically encode and recall music through a variety of sensory modalities—aurally, visually, and kinesthetically (see Ref. [47] for a review). Based on large-scale interview studies with professional musicians and a range of other empirical work, Williamon et al. [47,49,50] have argued (1) that the association of retrieval cues to encoded musical information through various modalities is largely individual-specific (e.g. one musician may rely more on visual associations, while another may rely more on aural) and (2) that musicians are likely to rely on more than one modality throughout the same piece of music (e.g. cues within a composition may have strong aural associations at some points, visual associations at others, and kinesthetic associations at still others). In the interview following each performance, participants were asked to rate (from 1=not at all to 7=exclusively) the "extent to which they relied on aural, visual, and kinesthetic memory when learning and performing the prelude." Mean ratings were, respectively, 5.50 (S.D.=1.38), 4.67 (S.D.=1.21), and 5.67 (S.D.=0.82). A subsequent repeated measures analysis of variance (ANOVA) with "memory type" as the within-subjects independent variable revealed no significant difference in these ratings, indicating a more-or-less equal preference for all three modalities among this group of pianists.

In this study, participants' memory for the music was tested using a visual recognition memory task; the reasons for this were twofold. First, most Western classical musicians begin learning and practicing new pieces from a notated source, which can form an important foundation for memory. As such, a visual task was deemed to be a realistic,

Fig. 1. Examples of structural, non-structural, and non-prelude bars presented to participants as part of the stimulus set. The entire set consisted of the 32 prelude bars and a matched set of 32 non-prelude bars.

widely experienced method for eliciting musical information. Second, visual stimuli were chosen specifically over auditory stimuli because the auditory presentation of music presents at least one major methodological limitation, in that music is a time-dependent domain. In the absence of a sizeable body of research in this area, it is not entirely clear whether emergent behavioral and psychophysiological data would actually be meaningful when participants must wait for properties of each stimulus to unfold over time.

In the visual recognition memory task, which took place within a week of each pianist's memorized performance, single bars from the prelude and matched bars (in terms of time signature, key signature, note durations, and melodic contour) not contained in the prelude were presented sequentially on a computer screen. Participants were required to indicate whether the bars belonged to the prelude or not by pushing buttons on a response pad with their left and right index fingers as fast as possible while maintaining accuracy. Mapping of button pushes to responses (e.g. right button for "yes," left button for "no") was counterbalanced across subjects. The stimulus set consisted of the 32 prelude bars and a matched set of 32 non-prelude bars, each presented four times in randomized order, resulting in 256 trials overall, including 32 structural bar trials and 96 non-structural bar trials (see Fig. 1 for examples of structural, non-structural, and non-prelude bars). Stimuli were presented for 1 s with an inter-stimulus interval of 4 s. The pictorial stimuli were presented on a black background in the center of a 36-cm monitor screen, and were of 7.5 cm height and 26–29 cm width. Stimulus presentation and response recording were achieved via the Neuroscan STIM interface (Compumedics, VIC, Australia).

2.5. EEG recording

EEG was recorded in an electrically shielded chamber via a 28-channel Electro-cap (ECI), placed in accordance with the international 10–20 system, on a Neuroscan Synamps system (Compumedics, VIC, Australia), and data processing and analyses were carried out with Neuroscan software (version 4.2). A ground electrode was placed 1.5 cm anterior to the central frontal electrode (FZ), and scalp electrodes were referenced off-line to a linked earlobe reference. Signal was acquired and digitized at a sampling rate of 500 Hz and passed through a 0 to 100 Hz bandpass filter (24 dB/octave roll-off). Electrode impedances were kept below 10 kΩ. The electrooculogram (EOG) was recorded with tin cup electrodes placed on the orbis occularis muscle above and below the left eye, and on the left and right outer canti, approximately 1 cm lateral to either eye. An EOG artefact correction algorhythm for removing eye-blinks and horizontal and vertical eye-movements [14] was applied to the EEG data off-line.

EOG-corrected data were epoched into 1122 ms intervals around each stimulus presentation (−10–1022 ms) and baseline-corrected with respect to a 100 ms pre-stimulus interval. Epochs containing amplitude fluctuations exceeding ±100 μV were rejected as artifact-contaminated. Event-related potentials from correctly identified prelude stimulus trials were averaged according to their hypothesized status into structural and non-structural bars and used for statistical analyses, along with averaged correctly identified non-prelude bars.

3. Results

3.1. Behavioral data

Mean reaction time (RT) and accuracy data are presented in Table 1. A priori nonparametric paired samples comparisons (Wilcoxon Signed Ranks test) revealed significantly faster RTs for structural than for non-structural bars ($p<0.05$), and a trend toward higher accuracy for identifying structural bars ($p=0.125$). Incidentally, there were no significant differences in response time or accuracy between prelude bars (either structural or nonstructural) and non-prelude bars.

3.2. ERP data

Visual inspection of the grand mean ERPs (see Fig. 2) across the whole scalp disclosed an early negative peak (50–150 ms) followed by an early positive peak (150–250 ms), and a late negative peak (250–400 ms), again followed by a late positive peak (400–550 ms). Peak amplitude and latency values for these time intervals were detected for each participant's responses to structural and non-structural bar stimuli, as well as to non-prelude bars, and employed for statistical analyses. For determining potential effects of bar type, time interval, and scalp topography on these peak amplitudes, amplitude values were first averaged across scalp electrodes grouped into left frontal (FP1, F3, F7), right frontal (FP2, F4, F8), left central (C3, CP1), right central (C4, CP2), left temporal (T3, T5, TCP1), right temporal (T4, T6, TCP2), left parietal (P3, PO1), right parietal (P4, PO2), and occipital (O1, O2, OZ) regions. Then mean ERP peak amplitudes for these sites, along with amplitudes for the midline sites FZ, CZ, and PZ, were entered into a 12 (scalp sites)×4 (time interval)×3 (bar type) repeated measures ANOVA. Greenhouse–Geisser corrections of degrees of freedom were applied where necessary, and the significance levels corrected accordingly. Identical analyses were carried

Table 1
Reaction times (RT) and percentage of correctly identified stimuli (accuracy) for stimulus categories (S.D. in brackets)

	RT	Accuracy
Prelude bars	1037 (231)	84.2% (12.5)
Structural bars	1010 (237)	89.9% (9.8)
Non-structural bars	1145 (449)	82.2% (15.1)
Non-prelude bars	975 (137)	90.3% (5.3)

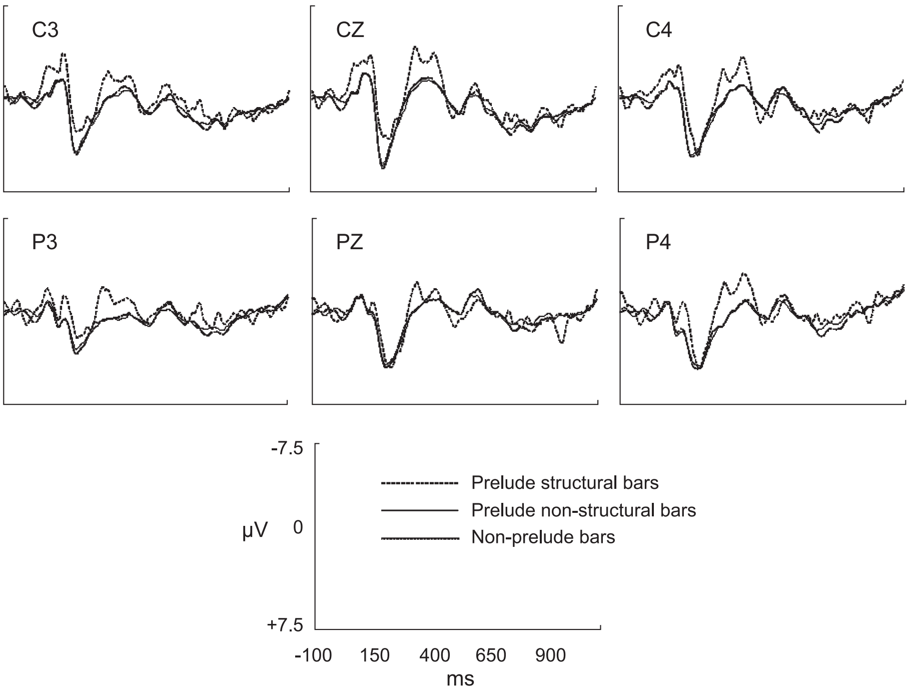

Fig. 2. Grand mean average ERP waveforms elicited by structural and non-structural prelude bars, and non-prelude bars, recorded from central and parietal scalp electrodes.

out for the ERP peak latency data. Only effects of interest, involving the factor of bar type, are reported.

No three-way interaction effect was detected, and there was no scalp site×bar type interaction effect. However, results revealed a significant time interval×bar type interaction effect ($F[3, 6]=5.73$, $p<0.001$) on peak amplitudes. Separate 12 (scalp sites)×3 (bar type) repeated measures ANOVAs at the different time intervals were run. While no significant effects of bar type or bar type×scalp site interaction effects were found in the early positive or late positive intervals, a significant effect of bar type was detected at the late negative peak ($F[1, 5]=10.15$, $p<0.05$), and the effect of bar type exhibited a trend toward significance in the early negative interval ($F[1, 5]=5.56$, $p=0.065$). As can be seen in Fig. 2, this interaction effect was due to significantly greater late negative peak amplitudes in response to structural bars than to non-structural bars ($F[1, 5]=9.99$, $p<0.05$) and to non-prelude bars ($F[1, 5]=10.31$, $p<0.05$). The trend in the early negative component shows the same pattern, albeit non-significantly ($p=0.065$; $p=0.064$). Although there was no bar type×scalp site interaction effect at the late negative peak, we explored the topography of our effect of interest (structural versus nonstructural bars) through paired-sample t-tests between structural and non-structural bar amplitudes at each of the scalp sites. These analyses disclosed significant differences

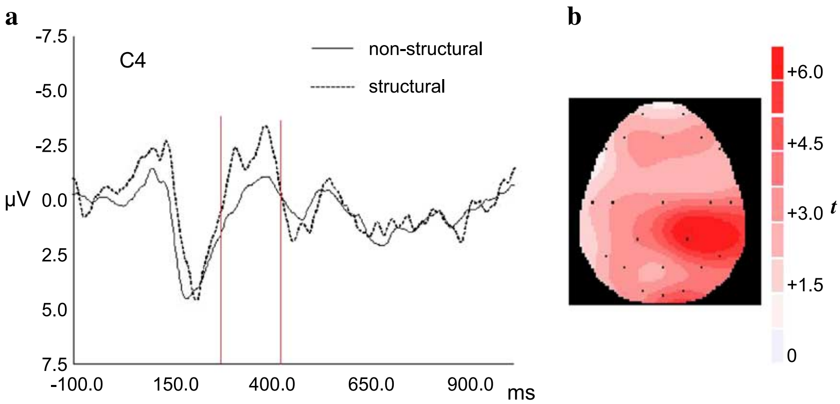

Fig. 3. (a) Representative ERP traces elicited by structural versus non-structural prelude bars at the right central C4 electrode site. Red vertical lines indicate the time interval for the late negative peak, which showed a significantly higher amplitude towards structural bars. (b) The topography of the late negative peak amplitude differences between structural and non-structural bars is plotted as a function of t-values over electrode sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the late negative peak at CZ (t [df=5]=2.69, $p<0.05$), right central (t [df=5]=4.39, $p<0.01$), right temporal (t [df=5]=3.82, $p<0.05$), left parietal (t [df=5]=2.87, $p<0.05$), right parietal (t [df=5]=3.53, $p<0.05$), and occipital sites (t [df=5]=3.13, $p<0.05$). Fig. 3a depicts this effect at electrode site C4, and in order to visualize the topography of the effect, in Fig. 3b the differences between structural and non-structural late negative ERP amplitudes are plotted as a scalp map of t-values of comparisons at each electrode site (using the headmap feature of the Neuroscan 4.2. software). It can be seen that the effect was particularly pronounced at right central and posterior scalp sites. Exploratory post-hoc analyses were also carried out between structural and non-structural bars at the early negative time interval, and paired-sample t-tests showed significant effects at left frontal (t [df=5]=2.58, p=.05), right frontal (t [df=5]=3.13, $p<0.05$), left central (t [df=5]=2.76, $p<0.05$), and left temporal (t [df=5]=3.45, $p<0.05$) electrode sites. While both negative ERP peaks show higher amplitudes toward structural bars, the waveform of structural bar ERPs did not display an overall negative shift compared to non-structural and non-prelude bars (see Fig. 2). Furthermore, the late negative peak effect and the trend at the early negative peak were independent of each other, as determined by bivariate correlation analyses (r=0.20, $p>0.5$).

When carrying out a 12 (scalp sites)×4 (time interval)×3 (bar type) repeated measures ANOVA on the ERP latency data, no significant effects were detected.

4. Discussion

The results of this study confirmed the hypothesis that bars of music that are putatively crucial for memory encoding and retrieval of a piece of music are processed differently from other bars within a memorized piece. On a forced choice recognition memory task, correct identification of structural bars was found to be significantly faster (and tended to display higher accuracy) than recognition of non-structural ones. Furthermore, in comparison with non-structural bars, as well as with non-prelude bars, recognition of structural bars was associated with a significantly greater negative ERP peak at a latency of around 300–400 ms post-stimulus, displaying a right centro-parietal scalp distribution, and with a tendency toward greater peak negativity within the 50–150 ms window, here displaying strongest effects at left temporal electrodes. Interestingly, these effects did not correlate with each other.

In terms of theories of expert memory, this study confirms several predictions of the Long-Term Working Memory (LT-WM) framework for music cognition. In particular, it supports earlier work in music (e.g. Refs. [8,50]) which demonstrated that musicians form and rely on highly ordered retrieval structures when recalling the compositions they memorize. In this case, as with previous studies, the data suggest that the salient components of the musicians' retrieval structures (i.e. the retrieval cues) coincided with the composition's structure. Indeed, the findings show that structural bars were accessed more quickly and in a qualitatively different way than the other encoded musical information. To the authors' knowledge, the identification of an ERP component that appears to be related to the retrieval of a semantic stimulus that had previously played an important role in creating an encoding and retrieval structure for memorizing a complex, meaningful sequence of stimuli constitutes a novel finding. We argue this ERP to be related specifically to the retrieval and recognition of stimuli that have a special mnemonic status within the memorized material, as this mid-latency negativity is qualitatively and conceptually different from episodic recognition memory effects (the old/new effect), from effects of memory trace strength and purely visual recognition processes, and from the classic N400 ERP.

The old/new ERP is typically derived from comparing responses to new versus previously studied word-list items, and responses to familiar items are characterized by a *positivity*, peaking over left parietal scalp regions (e.g. Ref. [41]). In contrast, the current study primarily compared responses between items that were all correctly identified as "old," but differed with respect to their purported importance to memorizing a complex sequence of stimuli. Reference to the traditional old/new paradigm, however, may help to delineate the meaning of the current results. Here, stimuli of importance to the retrieval structure of the learned "old" stimuli were characterized by a significantly greater event-related *negativity* than other "old" but mnemonically less relevant stimuli, peaking over right central and parietal scalp areas. Structural bars were also significantly more negative during this time window than "new" non-prelude control bar stimuli, with no difference between non-structural prelude bars and non-prelude bars. Therefore, the late negative ERP effect in the current study in our view cannot be accounted for by an old/new episodic recognition memory effect.

It could be argued that, while all prelude bars may be "old" stimuli to the pianists, the present paradigm simply represents a comparison between items of differing memory trace strength (due to a higher rate of repeated practice centered around the structural bars), rather than indexing some characteristic unique to stimuli that are structurally important to memorizing of the whole piece. This appears unlikely, however, as a recent study that contrasted ERPs between stimuli of graded memory strength (word items that were studied either once or three times) reported *less* negativity in response to strongly learned stimuli in the N400 time window [23]. This memory strength effect was most pronounced at left parietal electrodes. Similarly, ERPs of correctly identified items that had been deeply encoded have been shown to exhibit stronger parietal positivity than shallowly learned items [42]. As subjects recognized the structural bars more rapidly than the non-structural ones, it may be tempting to conclude that the observed ERP difference between the two could simply relate to varying latencies in the decision-making/response processes. However, the fact that structural bars displayed the same ERP effect with respect to non-prelude bars while not differing in recognition reaction times precludes this interpretation.

In addition, our interpretation of the late negative ERP component in the current study as representing processes related to semantic memory retrieval could be challenged on the grounds that the structurally important bars may have elicited a stronger visual recognition effect, as presumably they were subject to more extensive visual processing during the learning phase than the non-structural bars. Again, this interpretation appears untenable as far as the late negative component is concerned, as the structural bars' ERPs did not exhibit an old/new effect with respect to either the non-structural or the non-prelude stimuli. Thus, the late negative ERP effect for structural bars found in the current study may better be interpreted as reflecting these bars' special status as cues within the retrieval structure of the learned piece of music, eliciting a "conceptual" rather than a "perceptual" recognition effect. On the other hand, the fact that an independent trend for an early negative peak difference between structural and non-structural bars was obtained underlines the possibility that the structural bars were processed as more salient even at a stage where semantic identification of a complex visual stimulus appears unlikely. Therefore, the ERP to structural bars may reflect differences in both early perceptual (i.e. visual) recognition processes and preferential retrieval of stimuli that are of importance to the mnemonic structure of the learned piece of music. Eventually, the best test for determining whether the obtained effect arises from semantic rather than visual recognition memory processes would be to vary drastically the appearance of the learned stimuli during the recognition task or present them in the auditory modality.

Interestingly, the late ERP component identified in the current study displays a marked similarity to the latency and scalp topography of the N400 component discovered in the study of language comprehension [33]. However, as the N400 is elicited by violation of semantic context and its amplitude varies as a function of difficulty of semantic integration of a particular word into a sentence [32] (see Ref. [29] for a review), the ERPs stemming from structural bar recognition clearly seem to be conceptually unrelated to this component. If the current study has indeed successfully described a novel ERP component, it will have to be verified in future replications, where it should be of particular interest whether this component proves to be content-specific to musical memory structures or generalizes, for example, to structural word cues for memorizing text information such as poems.

Additionally, before further conclusions can be drawn about the neural foundations of musical memory—or of expert memory more generally—additional research must be conducted with more participants and with stimuli drawn from other types of music. With regard to the latter point, the majority of studies in music cognition focus on the encoding, retrieval, expression, and communication of tonal music from the standard repertory of solo instruments (namely, the piano). It is well-documented that such music typically conforms to hierarchical and serial principles of organization, both of which also appear to be cognitive principles of wide generality [31,38,39] (see Ref. [49] for a discussion). The demands on musicians' memories, however, are not limited to the successful recollection of just those types of compositions. Rather, they must frequently learn and perform pieces that run counter to the tonal, rhythmic, and structural "rules" that have been established through the works of composers such as J.S. Bach, Mozart, Haydn, Brahms, Mendelssohn, and so on. Studying exactly whether and, if so, how performers form, organize, and exploit retrieval structures when learning and performing music that defies (or at least does not conform exactly to) convention should provide insight into characteristics of cognition that have enabled musicians to meet new and evolving demands for hundreds of years.

In conclusion, we have supplied behavioral and electrophysiological evidence for the hypothesis that expert musical memory is underpinned by the strategic use of structural bar cues for creating a retrieval architecture of a musical work. These structural cues are recognized with greater ease and are associated with different brain responses than correctly recognized stimuli that are not of importance to the memory structure. These data support the basic tenet of the LT-WM theory in that they provide evidence that expert musicians develop and exploit domain-relevant retrieval structures based on generally accepted characteristics of associative encoding and retrieval of information in LTM [18]. Moreover, they provide initial insight into how such experts are able to update and transform information in LT-WM rapidly, without compromising efficiency and reliability of retrieval [34].

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