Music increases frontal EEG coherence during verbal learning

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Abstract

Anecdotal and some empirical evidence suggests that music can enhance learning and memory. However, the mechanisms by which music modulates the neural activity associated with learning and memory remain largely unexplored. We evaluated coherent frontal oscillations in the electroencephalogram (EEG) while subjects were engaged in a modified version of Rey's Auditory Verbal Learning Test (AVLT). Subjects heard either a spoken version of the AVLT or the conventional AVLT word list sung. Learning-related changes in coherence (LRCC) were measured by comparing the EEG during word encoding on correctly recalled trials to the immediately preceding trial on which the same word was not recalled. There were no significant changes in coherence associated with conventional verbal learning. However, musical verbal learning was associated with increased coherence within and between left and right frontal areas in theta, alpha, and gamma frequency bands. It is unlikely that the different patterns of LRCC reflect general performance differences; the groups exhibited similar learning performance. The results suggest that verbal learning with a musical template strengthens coherent oscillations in frontal cortical networks involved in verbal encoding.
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Music can enhance a diverse array of cognitive functions, such as spatiotemporal reasoning [31,34], attention [7,20], and memory [6,12,17]. Text is remembered better when accompanied by music [42,47]. Music provides a helpful mnemonic for verbal learning throughout life, and most notably during early development and in educational settings [3]. Music also provides developmentally disabled students a helpful rehearsal mechanism for learning non-musical material [4,11,46]. Despite this growing body of evidence that music affects cognition, the neural substrates of that influence are not yet clear.

Theory [8,14] suggests that memory, including verbal memory [15], may be subserved by oscillations in recurrent networks within and between brain regions. Empirical evidence using the scalp electroencephalogram (EEG) supports this view. Increased multi-band spectral power in the EEG during encoding is associated with successful subsequent word recall. This "subsequent memory effect" has most notably been found in 4–8 Hz theta [10,19,32] and 35–50 Hz gamma frequency bands [32] and with

either enhanced or reduced spectral power in 8–13 Hz alpha sub-bands, depending on the sub-bands [10,18] and whether the material is presented in visual or auditory modality [43]. Increased theta coherence has also been associated with successful encoding [44]. However, these and most related studies have used only single opportunities to study and/or retrieve verbal material. Yet repeated study and retrieval has been shown to be helpful for successful retrieval [36,40,45] and may therefore provide a more ecologically representative test of learning.

One task involving repeated study/test learning is Rey's Auditory Verbal Learning Test (AVLT) [22], a supraspan verbal learning and memory task used in neuropsychological assessments. We used as an operational definition of verbal learning the transition from not being able to recall to being able to recall a word that is repeatedly presented in the AVLT. In an earlier study we found that verbal learning is associated with broadband increases in EEG power spectra and that music influences the topographic distribution of that increased spectral power [39]. The present study extends our previous research by examining spatial coherence in the EEG measured during the learning phase associated with successful recall after short- and long-delays.

We focused our EEG coherence analysis on frontal areas because neuroimaging studies suggest verbal encoding involves

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both prefrontal and medial temporal cortical areas [2,16,41] and scalp EEG more accurately reflects superficial than deep cortical activity. We hypothesized that learning that persists over short- and long-delays would be associated with a "learning-related change in coherence" (LRCC) in frontal EEG. In order to elucidate the extent to which music affects the neural activity associated with verbal learning, we compared the effect of spoken versus musical (sung) presentation on learning and subsequent recall of word lists.

We hypothesized that the temporally structured learning template provided by music would strengthen LRCC patterns in frontal EEG compared to conventional spoken learning. If confirmed it would suggest that the two modalities of verbal learning involve different forms of plasticity in synchronized cortical oscillations.

Subjects were 16 healthy right-handed volunteers with normal hearing and no history of neurological or psychiatric conditions. All subjects provided written, informed consent approved by the institutional review board. They were randomly assigned to one of two experimental conditions in a between-subjects design: with and without a musical mnemonic, hereafter referred to as the "spoken" and "musical" conditions. Subject age ranges were 18–26 yrs (mean = 19.8, S.D. = 2.8) for the "spoken" condition and 18–21 yrs (mean = 19.0, S.D. = 1.0) for the "musical" condition. Each group included seven females.

We administered the AVLT using pre-recorded sound files and remotely recorded voice responses with the subjects isolated in a sound-proof booth. Although the AVLT is typically administered in person, we used an automated design to maximize consistency of the test procedures and to avoid the increased risk of artifacts in the simultaneously recorded EEG that would normally accompany personal interaction. Our use of the AVLT and the associated definitions of learning and memory are depicted in Fig. 1. A single standard list of 15 semantically unrelated words was repeated in five learning trials L1–L5, and subjects asked to free recall as many words as possible after each list presentation. The words were presented at a rate of approximately one per second with identical presentation order on every trial. On each trial, subjects were instructed to listen carefully as they would subsequently be asked to recall the words, and that order

was not important. There was no feedback provided on any trials. In a sixth trial, subjects heard and were asked to free recall a new "distracter list" to test whether an increase in performance was merely a general time-dependent effect. Subjects were then given a 20-min visual attention distractor task. On the memory trials before (M1) and after (M2) the distracter task, subjects were asked to free recall the original list.

The spoken and music conditions used identical word lists of equal overall duration presented free field at 80 dB SPL. The sound files were recorded using the same female voice for both conditions. In the musical condition the word list was presented as lyrics for an originally composed song. We used a melody that was not familiar but was simple and repetitive in structure (AABA form). One-syllable words were assigned one-quarter note of 1 s duration, while two-syllable words were assigned one eighth note of 0.5 s per syllable to generate melodic–rhythmic phrasing and to keep the sung condition at 15 s durations.

Continuous EEG was recorded from 32 scalp electrodes with Neuroscan's QuikCap using low- and high-cutoff frequencies of 1 and 100 Hz, respectively, and a 1 kHz sampling frequency. Ocular artifacts in non-EOG electrodes were regressed out with Neuroscan's ocular artifact reduction [33]. We computed inter-electrode coherence over a 500 ms window starting 250 ms after each word's onset for all non-EOG electrode pairs in each of the theta (3–5), alpha (7–9), and gamma (35–50 Hz) frequency bands. Coherence C_{ij} between each pair of electrodes i and j was defined as the magnitude squared of the cross spectral density between electrodes i and j normalized by the product of the two electrodes' individual power spectral densities, with spectral densities calculated with a standard discrete Fourier transform.

We defined the learning-related change in coherence (LRCC) as the percent increase or decrease in coherence comparing "first recalled" words to the same words not recalled during the immediately preceding trial (see Fig. 1, thick arrows). The LRCC was computed from all pairs of not-learned/learned words that met this operational definition of learning. Outliers (in the case of very low coherence in the preceding trials, less than 5% of the data) were clamped at 300% increase. We analyzed LRCC for words with respect to their subsequent successful retrieval during the two memory trials [39], thereby characterizing learn-
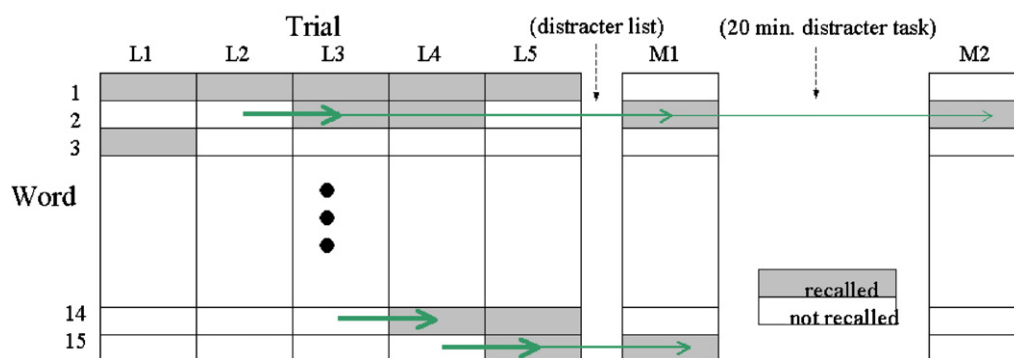

Fig. 1. Rey's Auditory Verbal Learning Test (AVLT) and the operational definitions of:

- learning (thickest arrows, during the learning trials—e.g. words 2, 14, 15);
- short-delay memory (medium thick arrows to M1—e.g. words 2, 15);
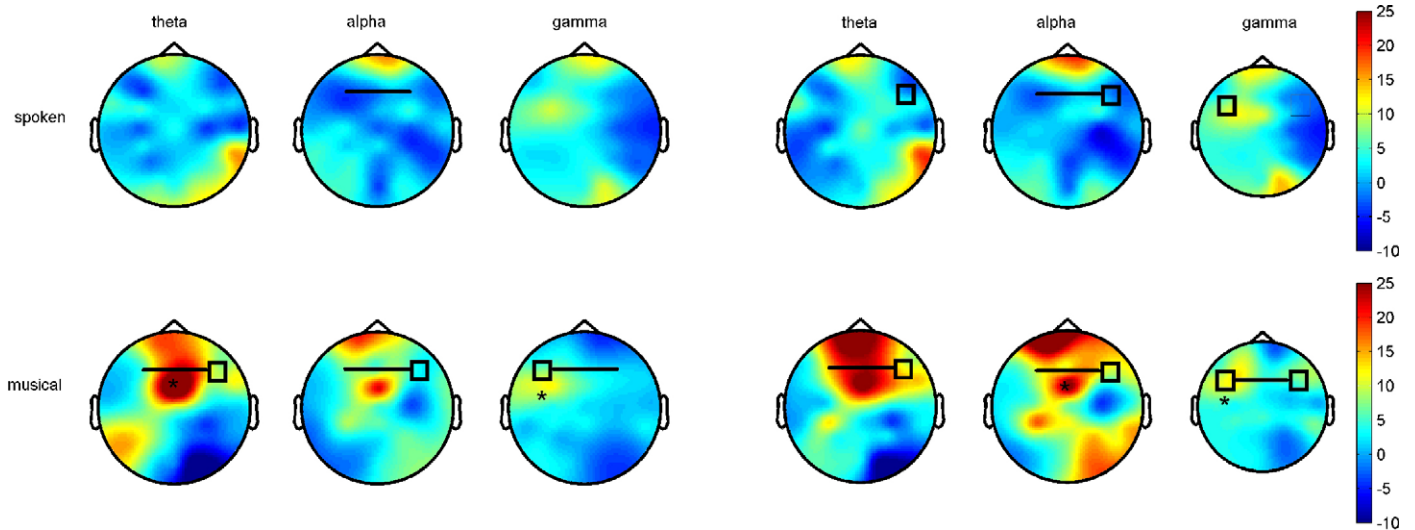- long-delay memory (thinnest arrows to M2—e.g. word 2).

Fig. 2. Learning-related change in coherence (LRCC). Left: LRCC for short-delay recall; right: LRCC for long-delay recall. Scale bar is percent change. Straight line and box overlays indicate absolute changes in LRCC greater than 5%: box for local quadrant LRCC, and line for interquadrant (interhemispheric) LRCC. Thin box (e.g. spoken group's long-delay right frontal gamma LRCC) indicates a decrease of greater than 5%.

ing associated with successful recall over the short- (M1) and long-delay (M2) memory trials. In the spoken condition, there were 43 instances of learning with short-delay recall and 37 with long-delay recall. There were 40 and 31 such instances in the music condition. LRCC was calculated individually for every subject then combined across subjects and trials by condition and group. For each frequency band, we compared the LRCC averaged across subjects in each group to the null hypothesis that there would be a zero percent change associated with initial learning.

For qualitative comparison, we plotted global topographies of the local LRCC by averaging each electrode's coherence with adjacent electrodes, spatially smoothed by interpolating between electrodes. We used three adjacent electrodes to mitigate undue influence of individual electrode pairs while preserving topographically localized coherence information. For quantitative comparisons, we computed local coherence within the left and right prefrontal areas (i.e. FT7, F7, and F3 on the left, and FT8, F8, and F4 on the right) and the network coherence between them. For the intrahemispheric coherence measure, we used the mean coherence between the three pairings of three electrodes in the left and right prefrontal areas. The interhemispheric coherence measure was based on the mean coherence between the nine pairs of the two sets of three electrodes. LRCC for each group were compared to no change using one-tailed

T-tests, alpha = 0.05. LRCC between the two groups were compared using two-tailed T-tests, alpha = 0.05. Results are reported before Bonferroni adjustment by factor of three for multiple comparisons.

Both groups recalled roughly six more words on the last learning trial than on the first (means of 11.0 and 4.9 for the spoken group, 9.7 and 4.3 for the music group), corresponding to a statistically significant improvement in performance, $t(16) = 9.6$ and 6.3, respectively, $p < 0.0001$. The overall pattern of performance agreed with normative data [22]. Recall was not significantly different between the spoken and musical groups on any trial, all $t(16) < 1.4$ and $p > 0.1$.

Fig. 2 shows the learning-related change in coherence (LRCC, as percent change in coherence) averaged across trials for all subjects in each group. The qualitative LRCC is depicted in the interpolated color plots. The music group had generally higher LRCC than the spoken group, particularly in frontocentral theta and alpha bands. For both groups and in all three frequency bands, the LRCC in the long-delay learning appears slightly more intense (either in amplitude or breadth of distribution, or both) than in the short-delay learning.

Quantitative results are provided in Table 1 and illustrated with overlays on the LRCC topographies in Fig. 2. Spoken verbal learning involves a mix of positive and negative LRCC, but none of the LRCC values differed significantly from zero.

Table 1
Frontal learning-related change in coherence (LRCC)

	Short memory			Long memory		
	L	L <--> R	R	L	L <--> R	R
Theta	99 (7) 100 (3)	102 (9) **134 (13)**	103 (7) 116 (8)	102 (8) 102 (3)	98 (8) 125 (13)	104 (8) 116 (9)
Alpha	97 (5) 102 (3)	107 (9) 124 (10)	98 (2) 110 (6)	99 (6) 102 (3)	109 (10) **138 (12)**	97 (3) 119 (9)
Gamma	104 (4) **110 (3)**	101 (5) 107 (4)	96 (2) 103 (4)	105 (4) **111 (4)**	101 (5) 110 (5)	95 (2) 111 (6)

In each cell: $\boxed{\text{SPOKEN}_{mean}\ (_{stderr})\quad \text{MUSIC}_{mean}\ (_{stderr})}$. Values are mean coherence relative to previous unlearned trial (i.e. 100 is no change in coherence). Bold values indicates $p < 0.05$ in one-tailed T-test after Bonferroni correction. Highlighted values indicates $p < 0.05$ in between-group, two-tailed T-test after Bonferroni correction.

Only a negative right frontal gamma LRCC approached statistical significance ($t(42) = 2.2$, $p = 0.03$ and $t(36) = 2.2$, $p = 0.03$ for short- and long-delay learning, respectively). In contrast, musical verbal learning involved positive LRCC within and between the hemispheres. For short-delays, the increased frontal coherence was significant in left gamma ($t(39) = 3.2$, $p = 0.003$) and interhemispheric theta ($t(39) = 2.6$, $p = 0.01$). For long-delays, the increased frontal coherence was significant in left gamma ($t(30) = 3.1$, $p = 0.005$) and interhemispheric alpha ($t(30) = 3.1$, $p = 0.004$).

Between group comparisons are also provided in Table 1. LRCC was higher for the music group than the spoken group in all three frequency bands. The music group exhibited a greater increase in theta coherence between the hemispheres for both short- and long-delay learning, nearly reaching significance for short-delay learning ($t(81) = 2.1$, $p = 0.04$). The music group also exhibited an increase in right alpha coherence, and the spoken group a decrease, for both short- and long-delay learning, nearly reaching significance for long-delay learning ($t(66) = 2.5$, $p = 0.01$). There was a significant difference in right gamma coherence between the groups for long-delay learning, with the musical group exhibiting increased coherence and the spoken group decreased coherence ($t(66) = 2.7$, $p = 0.009$).

We investigated the effect of music as a temporally structured mnemonic on the neural plasticity associated with verbal learning and memory. For the music group, learning that produces persistent retention across interference and delay was associated with changes in the scalp-recordable coherence of oscillatory brain processes. The changes in coherence during word learning provide evidence that learning-related cortical plasticity is manifest as changes in synchronous oscillatory processes. The finding is consistent with an earlier study in which cognitive learning associated with repetitive practice effects in working memory produced changes in the EEG spectra [24]. The increased gamma synchrony we found associated with musical verbal learning is also consistent with other studies that have found increased gamma associated with working memory rehearsal [37].

Verbal learning with a musical template involved an increase in frontal coherence whereas there was no significant change in coherence associated with spoken verbal learning. Subjects learning the sung version of the word list demonstrated stronger temporal synchronization in prefrontal areas than subjects learning the spoken version. While further studies with a greater number of subjects are needed, the findings provide evidence that verbal learning with a musical template induces a different form of plasticity than conventional verbal learning, inducing strengthened synchronous oscillations in prefrontal cortical networks. The lack of change in coherence in conventional verbal learning does not, however, mean that such learning does not involves changes in brain oscillations. Thaut et al. [39] report increased broadband spectral power associated with conventional verbal learning. Thus, it may be that both forms of verbal learning involve strengthened cortical oscillations, with conventional verbal learning involving more focal changes and musical verbal learning involving topographically broader network synchronization.

Although music has been shown to improve learning and memory in a number of other studies, music did not enhance learning and memory performance in this study. A potentially beneficial effect of music may have been nullified in this study by the change in recall modality; subjects in both groups were asked to recall the words in spoken fashion. Transfer appropriate processing theory [26] would suggest that performance would be enhanced if subjects recalled material in the same way it is encoded. Nevertheless, the groups' similar behavioral performance suggests that differences in physiological results are not merely due to differences in performance. Furthermore, our physiological measure, the change in learning-related coherence, is by definition normalized by the same word in the previous trial. Thus, differences between the groups' physiological results are not due to the differential sensory processing of spoken versus musical stimuli.

It remains unclear how music may affect the synchronization of network oscillations in the brain. A number of possibilities can be put forth. (1) A musical template may influence word encoding through an early attentional mechanism. Selective attention is associated with increased coherence at multiple spatial scales, as measured both invasively and in scalp potentials [27]. (2) Enhanced expectancy may contribute to the higher increase in coherence in music condition. The regular temporal structure of music is known to induce a form of expectancy in which listeners can predict aspects of the immediately forthcoming part of the music, and pre-stimulus expectancy is associated with synchrony between individual spikes and local field potentials in monkey V4 [9]. (3) Coherent synchronizations may help bind word object representation to its "place" in the musical template, akin to the hypothesized role of coherent gamma oscillations in binding an object's early sensory features. Both associative learning [25] and music perception [1] are associated with increased gamma synchronization. (4) Scalp-recorded differences in coherence could reflect a broader network recruitment with music. Lesion [13,29], functional imaging [28,48], EEG [30] and MEG [23,38] studies have suggested that music-related processing in the brain involves cortical and subcortical networks that are more widely distributed than non-musical verbal function.

The results of the current study provide some of the first evidence that music as a mnemonic device for non-musical learning strengthens coherent brain oscillations associated with verbal learning. Earlier work puts forth models of music's influence on higher cortical function [21]. In an important step toward elucidating music's influence on cognitive functions in the brain, the present study supports the idea that the synchronous activity of multiple cortical areas may play a role in defining functional cell assemblies involved in music-facilitated verbal learning [35].

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