Spatial vision is superior in musicians when memory plays a role

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Musicians’ perceptual advantage in the acoustic domain is well established. Recent studies show that musicians’ verbal working memory is also superior. Additionally, some studies report that musicians’ visuospatial skills are enhanced although others failed to find this enhancement. We now examined whether musicians’ spatial vision is superior, and if so, whether this superiority reflects refined visual skills or a general superiority of working memory. We examined spatial frequency discrimination among musicians and nonmusician university students using two presentation conditions: simultaneous (spatial forced choice) and sequential (temporal forced choice). Musicians’ performance was similar to that of nonmusicians in the simultaneous condition. However, their performance in the sequential condition was superior, suggesting an advantage only when stimuli need to be retained, i.e., working memory. Moreover, the two groups showed a different pattern of correlations: Musicians’ visual thresholds were correlated, and neither was correlated with their verbal memory. By contrast, among nonmusicians, the visual thresholds were not correlated, but sequential thresholds were correlated with verbal memory scores, suggesting that a general working memory component limits their performance in this condition. We propose that musicians’ superiority in spatial frequency discrimination reflects an advantage in a domain-general aspect of working memory rather than a general enhancement in spatial-visual skills.

Introduction

Musicians are known to have exceptionally high auditory frequency discrimination abilities (Kishon-Rabin & Amir, 2001; Micheyl, Delhommeeau, Perrot, & Oxenham, 2006; Schellenberg & Moreno, 2009; Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005). This perceptual advantage in the acoustic domain is not surprising because musicians practice related tasks and probably have elevated sensitivity even before commencing their massive practice (Hyde et al., 2009a, 2009b; Norton et al., 2005; Schlaug et al., 2009).

Yet musicians’ reported superiority is not limited to acoustic discriminations. The extent and cause of their advantage is still debated. Several studies reported that early musical training may enhance verbal skills, particularly verbal memory (e.g., Chan, Ho, & Cheung, 1998; Franklin et al., 2008; Jakobson, Cuddy, & Kilgour, 2003). Other studies suggested that musical
training boosts cognitive abilities in a broad manner (e.g., Bergman Nutley, Darki, & Klingberg, 2014; reviewed in Jacoby & Ahissar, 2013). Although enhancement of verbal span may be attributed to shared storage of verbal and nonverbal auditory stimuli, accounting for broader differences assumes the involvement of more central mechanisms. A prime candidate for musicians’ broader underlying advantages is enhanced working memory. The term “working memory” refers to the mechanisms that underlie our ability to retain and manipulate information simultaneously (e.g., Baddeley, 1996). The efficiency of these mechanisms affects our planning and reasoning skills and also plays a role in perceptual and sensory-motor tasks, particularly when these require processing of sequentially presented stimuli (e.g., Broadway & Engle, 2011; Cho, Holyoak, & Cannon, 2007; Seidler, Bo, & Anguera, 2012; Süss, Oberauer, & Wittmann, 2002).

Thus, an enhancement of central working memory processes is expected to upgrade performance in many tasks that depend on sequential processing. Several studies suggested that this is indeed the case with musicians. For example, an event-related potential study that assessed responses during auditory and visual oddball detection found that musicians’ P300 response had a shorter latency. Because P300 is considered to indicate the timing of updating the content of working memory (i.e., “an oddball was just detected”), this observation was interpreted as implying that musicians’ rate of updating is higher than that of nonmusicians (George & Coch, 2011).

An intuitively surprising advantage attributed to music training is enhanced visual abilities, specifically in tasks of a visuospatial nature (e.g., Brochard, Dufour, & Desprès, 2004; Jakobson, Lewycky, Kilgour, & Stoesz, 2008; Patston, Hogg, & Tippett, 2007; Sluming, Brooks, Howard, Downes, & Roberts, 2007). A typical account for these observations is that musical training enhances the association between the dimension of pitch and spatial representations (Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Indeed, musicians’ visual areas are activated when they are asked to perform pitch discriminations (Platel et al., 1997; Schmithorst & Holland, 2003) and even in memory tasks that only involve verbal stimuli (Huang et al., 2010).

However, not all studies found that musical training is associated with enhanced spatial-visual abilities (e.g., Children: Ho, Cheung, & Chan, 2003; Mehr, Schachner, Katz, & Spelke, 2013; Adults: Chan et al., 1998; Cohen, Evans, Horowitz, & Wolfe, 2011; Douglas & Bilkey, 2007). This inconsistency can perhaps be attributed to the different nature of the tested tasks. For example, some tasks required maintenance and manipulation of the mental images (Forgeard, Winner, Norton, & Schlaug, 2008; Sluming et al., 2007) or sequential memory (Brochard et al., 2004; Jakobson et al., 2008; Patston et al., 2007) whereas others did not include a retention component (Hanna-Pladdy & Gajewski, 2012; Mehr et al., 2013). Additionally, some studies controlled for general reasoning abilities (Hanna-Pladdy & Gajewski, 2012; Sluming et al., 2007; Stoesz & Jakobson, 2007) whereas others did not (Brochard et al., 2004; Chan et al., 1998; Mehr et al., 2013). This type of control is important because general reasoning abilities may affect performance in perceptual tasks (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Wilhelm & Oberauer, 2006).

Current findings, therefore, do not dissociate between whether musicians’ visuospatial advantage reflects a visual advantage or a specific manifestation of better central working memory mechanisms (e.g., Bergman Nutley et al., 2014). To dissociate between these alternatives, we administered a spatial frequency task involving discrimination between two horizontal sinusoidal gratings. This is a basic visual discrimination task. Yet its underlying requirements depend on the mode of stimuli presentations (e.g., Ben-Yehudah & Ahissar, 2004; García-Pérez, Giorgi, Woods, & Peli, 2005; Giorgi, Soong, Woods, & Peli, 2004), namely, whether the two stimuli are presented simultaneously (spatial forced choice between the upper and lower parts of the screen) or sequentially (temporal forced choice between two consecutive presentations). The sequential condition has a clear working memory component (Baumann, Endestad, Magnussen, & Greenlee, 2008; Pasternak & Greenlee, 2005) because participants are asked to retain some features of the first stimulus (e.g., average “width” of a single cycle) and then compare them to the subsequently presented stimulus. The simultaneous condition enables comparison between the two stimuli without retention by using a more global form of observation that captures the direction of change in spatial frequency between the upper and lower parts of the screen.

This experimental design allowed us to compare three hypotheses. Hypothesis 1: Musicians have a general spatial-visual advantage. In that case, musicians would do better in both the simultaneous and the sequential discrimination conditions. Hypothesis 2: Musicians have an advantage in central working memory mechanisms. In that case, musicians would do better in the sequential but not in the simultaneous paradigm. Hypothesis 3: Musicians have no spatial-visual advantage. Neither their initial skills nor their experience are relevant to visuospatial tasks beyond the directly trained visual context of musical notes (Wong & Gauthier, 2012). In that case, musicians will have no advantage in any of the spatial frequency discrimination conditions.
We should note that for cases in which musicians perform better, our procedure does not allow a dissociation between cause and effect, namely, between musicians’ advantages being due to a selection bias (more cognitively competent individuals are drawn to and persist in musical training) compared with them being a consequence of their musical training (Corrigall, Schellenberg, & Misura, 2013; Schellenberg, 2011; Schellenberg & Weiss, 2013).

Musical background

The average number of years of formal musical training among musicians was 11.9 ± 3.5 years, and their average age when starting to take music lessons was 8.1 ± 3.2 years. Of the 42 participants in the musicians’ group, 12 studied piano, eight strings, and seven voice, and 15 studied wind instruments. Of the 33 participants in the group of nonmusicians, 20 had no musical education and 13 had some education but amounting to less than 3 years.

Behavioral procedures

Standard cognitive tests

General cognitive abilities were assessed by two subtests from the Hebrew version of the Wechsler Adult Intelligence Scale (WAIS-III): Block Design and Digit-Span (Wechsler, 1997). The Block Design task measures spatial reasoning abilities. We chose this specific reasoning test because it does not depend on verbal working memory (Banai & Ahissar, 2004), in which we expected that musicians might have an advantage. The Digit-Span test measures verbal working memory. It includes two parts: Digit-Forward—the participant is asked to repeat series of orally presented digits—and Digit-Backward—the participant is asked to repeat series of orally presented digits in reverse order. In both conditions, the length of the sequence of digits is gradually increased.

Syllable span

Verbal working memory was further assessed with a syllable-span test (Oganian & Ahissar, 2012). This paradigm was designed on the basis of the procedure for assessing forward Digit-Span in this WAIS subtest (Wechsler, 1997). Participants were presented with sequences of consonant-vowel syllables (a recording of a native Hebrew speaker) with increasing length and were requested to repeat the syllables in the presented order. Participants were presented with two sequences for each length, starting with two syllables; the task continued until the participant either failed in two sequences of the same length or reached the maximal sequence length of eight syllables. Each syllable appeared only once during the whole test. Performance was evaluated as the number of correctly reproduced sequences (score) and the number of syllables in the last correctly reproduced sequence (span).

Perceptual tasks

Auditory frequency discrimination: Perceptual thresholds for auditory two-tone frequency discrimination were measured using a two-alternative forced choice...
(2AFC) protocol. In each trial, two 50-ms pure tones were presented with an interstimulus interval of 950 ms. The frequency of the first tone was always 1000 Hz, and the second tone in each trial was either lower or higher. After hearing both tones, participants had to decide which tone had the higher pitch (frequency) and a visual feedback was given. Thresholds were assessed in blocks of 80 trials, using an adaptive three-down, one-up staircase procedure, converging to 79.9% correct (Levitt, 1971). The initial frequency difference was 20%. The step size was decreased every four reversals from 4.5% to 2% to 1% to 0.5% to 0.1%. Discrimination thresholds (just noticeable difference, JND) were calculated as the mean frequency difference in the last five reversals. The tones were presented binaurally through Sennheiser HD-265 linear headphones using a Tucker Davis Technologies System III signal generator controlled by in-house software in a sound-attenuated chamber in the lab. Tone intensity was 65 dB.

Spatial frequency discrimination: Perceptual thresholds for visual frequency discrimination were measured using a 2AFC protocol. Visual stimuli were presented on a Microtron screen with a frame rate of 100 Hz and a linear gamma correction. Mean luminance was 16 cd/m², and intensity ranged from 11 to 22.9 cd/m². The tasks were administered in a dark room and began after 2 min of dark adaptation. Subjects were instructed to look at the middle of the screen (there was no fixation point) and to indicate which grating was denser by pressing the appropriate button. An auditory feedback followed each response. Thresholds were assessed in blocks of 80 trials, using an adaptive two-down, one-up staircase procedure, converging to 71% correct (Levitt, 1971). The initial step size was 10%, and it was halved every three reversals (to a minimum of 1%). Discrimination thresholds (JND) were calculated as the mean frequency difference in the last five reversals.

The task was conducted under two different conditions, as illustrated in Figure 1:

1. The sequential (“Seq”) condition: Two horizontal sinusoidal gratings were presented sequentially, one in the first and the other in the second interval. Each grating subtended the whole screen (34 by 48 cm) and was presented for 250 ms with a 500 ms interstimulus interval (see Figure 1, left).
2. The simultaneous (“Sim”) condition: Two horizontal sinusoidal gratings were presented simultaneously for 250 ms, one in the upper and the other in the lower half of the screen. The size of each grating was 34 by 24 cm. They were adjacent and together subtended the entire screen (see Figure 1, right).

Each of these conditions was conducted using a fixed position reference protocol. In each trial, a grating stimulus of 0.2 c/° appeared. Under the “Seq” condition, this reference stimulus was presented in the first interval of each trial. Under the “Sim” condition, this reference was presented in the upper half of the screen. The other grating stimulus was chosen according to the staircase procedure described above.

The JNDS in both the auditory and visual tasks were power-transformed (logarithm) prior to all analyses. According to the Weber-Fechner law, the relationship between stimulus magnitude and perceived magnitude is logarithmic. Thus, after the transformation, scores can be compared in a linear model.

Order of assessment

Subjects participated in two sessions, each lasting ~1 hr. The first session included the cognitive and auditory tasks. The second session, administered a few days to a few months later, included the visual tasks. Each
participant was also tested on spatial-visual discriminations without a constant reference. The results reported here refer only to the tests with a fixed reference stimulus. All participants performed all assessments except the syllable-span task, which was performed by all musicians but only by 15 nonmusicians.

Results

Cognitive and reading profiles

Our exclusion criteria ensured that the two groups of participants were matched for general reasoning skills (measured by the standard Block Design task, WAIS-III) as shown in Table 1. Interestingly, musicians did not differ in their Digit-Span scaled score (in line with some previous reports; Lee, Lu, & Ko, 2007) even though musicians are reported to have elevated verbal working memory (e.g., Brandler & Rammsayer, 2003; Chan et al., 1998; Kilgour, Jakobson, & Cuddy, 2000) and indeed attained higher scores when syllable-span was measured.

Verbal working memory abilities

We further assessed verbal working memory with a syllable-span task, considered to assess phonological memory. This task is not affected by prior strategies because participants are naïve to this task. This task was performed by all our musician participants and by 15 of the nonmusicians. As expected, the musician participants attained significantly higher scores in their maximal span, nonmusicians: 6.06 ± 1.16, musicians: 6.9 ± 1.12, \( t(55) = -2.5, p = 0.017 \), and marginally higher scores in the total number of sequences they correctly repeated, nonmusicians: 9.33 ± 2.46, musicians: 10.5 ± 2.02, \( t(55) = -1.8, p = 0.076 \). As expected, scores obtained in the syllable-span task were correlated with Digit-Span scores (\( r = .78 \) and \( .52 \) for nonmusicians and musicians, respectively; \( p < 0.01 \) for both groups).

Auditory frequency discrimination thresholds

We first assessed the discrimination thresholds of each group in the auditory domain, in which we could only administer the sequential condition. We used a protocol that contains a reference tone in a fixed temporal position (the first tone in two-tone trials). As expected and shown in Figure 2, the thresholds of nonmusicians were significantly lower than those of musicians, \( t(73) = 5.04, p < 0.001 \).

We asked whether auditory discrimination thresholds were correlated with verbal span. Digit-Span was not significantly correlated with thresholds in either group (\( r = -.03 \) and -.19 for musicians and nonmusicians, respectively). Neither were scores obtained in the syllable-span task among musicians (\( r = .05 \)). Based on our previous studies (Oganian & Ahissar, 2012), we expected nonmusicians’ auditory thresholds to be correlated with their syllable span, but the number of nonmusician participants who performed this task was too small for a reliable evaluation of this correlation (\( r = -.34; n = 15 \); not significant).

All our auditory assessments were based on serial presentations. Therefore, one account for musicians’ general superiority in auditory tasks is general superiority in some aspects of serial processing, which may not be specific to auditory stimuli. The auditory modality does not allow direct testing of this interpretation because temporally overlapping stimuli yield a combined object rather than two separate items.

Spatial frequency discrimination thresholds

In the visual task, we could use two modes of presentation: sequential (“Seq”) and simultaneous (“Sim”). The sequential mode had the same structure as in the auditory modality (a fixed reference grating was always presented first). As shown in Figure 3A, the two groups did not differ in thresholds in the simultaneous condition.
The relationship between visual and cognitive abilities

To further probe the relationship between the mechanisms underlying the sequential and simultaneous conditions of spatial frequency discrimination, we examined the correlations between scores in the different visual protocols. As shown in Table 2, the two conditions of spatial discrimination (“Sim” and “Seq”) were correlated only among musicians whereas among nonmusicians there were no significant correlations between the “Sim” and “Seq” conditions. This observation suggests that a common bottleneck limits musicians’ performance in the two conditions of the visual task whereas different bottlenecks limit nonmusicians’ performance in the “Sim” and “Seq” conditions.

A complementary pattern was found in the correlation between performance in spatial frequency and verbal working memory (assessed with Digit-Span). Nonmusicians’ performance in the sequential condition was correlated with memory span whereas musicians’ was not. This result suggests that nonmusicians’ performance of the sequential task is limited by a domain-general memory bottleneck whereas musicians’ performance is not limited by this bottleneck.

Taken together, this combined pattern of correlations (Table 2) suggests that musicians’ spatial frequency discrimination is limited by their visual skills (and not by their memory skills) whereas nonmusicians’ performance in sequential presentations is limited by a domain-general aspect of their working memory skills.

We further examined whether the visual thresholds were correlated with auditory thresholds or with general reasoning scores. Neither auditory thresholds nor general reasoning abilities were correlated with visual thresholds in either group. Because only a small (n = 15) number of nonmusician participants performed the syllable-span task, we did not calculate correlations for this task.

Musical training and perceptual abilities

Given that musicians had better thresholds in the auditory tasks and in the visual sequential task, we tested whether performance in these tasks was correlated with age commencing music studies or with the extent (number of years) of musical training. We found that only the auditory task was correlated with age commencing music studies (Pearson: \( r = 0.47, p = 0.001 \), Spearman: \( r = 0.56, p < 0.001 \)) and with the extent of musical training (Pearson: \( r = -0.42, p = 0.005 \), Spearman: \( r = -0.51, p = 0.001 \)). Neither of the two visual tasks was found to be correlated with these measures of musical training.
Discussion

Summary of results

We found that spatial frequency discrimination was superior in musicians compared with nonmusician peers matched for age and general intelligence in a specific condition. Musicians performed better only when tested in a two-alternative sequential (rather than simultaneous) forced choice. Nonmusicians’ thresholds in the simultaneous and sequential versions of this task were not correlated. By contrast, their thresholds in the sequential condition were correlated with their verbal memory scores (Digit-Span). This pattern of correlations suggests that shared mechanisms limit nonmusicians’ performance in sequential spatial frequency discrimination and verbal working memory tasks. Such processes may be domain-general aspects of working memory. On the other hand, musicians’ thresholds in the two visual conditions were correlated, suggesting that shared mechanisms, probably within the visual pathways, limit their performance in the two conditions of this task. Musicians’ specific advantage in the sequential discrimination condition perhaps results from an advantage in some aspect of their domain-general working memory mechanisms.

Our findings and interpretation clarify previous inconsistencies. Most previous studies that found enhanced spatial-visual abilities among individuals with musical training were based on tasks that required maintenance and manipulation of mental images (Jakobson et al., 2008; Sluming et al., 2007) or processing of sequential presentations (Brochard et al., 2004; Patston et al., 2007). However, no advantage in spatial-visual abilities was mainly reported for tasks that did not include a retention component (Mehr et al., 2013) or did not control for reasoning abilities (Chan et al., 1998; Ho et al., 2003).

Sequential spatial frequency discrimination and working memory

The finding that performance of the general population (nonmusicians) in the same visual task is not correlated across different assessment conditions has broad implications. Psychophysicists typically choose an assessment procedure quite arbitrarily. The sequential 2AFC paradigm is often used to assess visual thresholds (e.g., Gescheider, 1997; Macmillan & Creelman, 2005). We now find that because this procedure requires a comparison between two sequentially presented stimuli, it involves central working memory mechanisms for retaining and comparing the stimuli, which pose additional nonsensory limitations (e.g., Romo, Hernández, & Zainos, 2004; Zaksas & Pasternak, 2006). This aspect is typically ignored, and visual tasks are addressed as if they directly measure sensory bottlenecks.

The finding that serial visual processing depends on working memory mechanisms is not new. However, it was previously noted for special populations. For example, individuals with reading and language difficulties (dyslexics), known to have poor verbal working memory, perform the sequential but not the simultaneous forced choice condition worse than their peers (Ben-Yehudah & Ahissar, 2004; see also Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001, for a similar finding in contrast detection). We now find that central mechanisms pose a nonsensory bottleneck to performance even in the general population.

Musicians and sequential processing

Our findings suggest that the “mirror symmetry” between musicians’ advantages and dyslexics’ disadvantages compared with the general population, which was previously reported for verbal working memory (e.g., Chandrasekaran & Kraus, 2010; Tsouopoulos & Kraus, 2009), also applies for sequential visuospatial tasks. Namely, musicians score better than the general population whereas dyslexic individuals score worse in these tasks when either verbal or visual sequential tasks are assessed. These observations suggest that memory process that are impaired in dyslexia are enhanced among musicians.

One account for musicians’ advantage is that it is obtained as a consequence of their musical training. This interpretation is consistent with the Scaffolding Hypothesis, proposed by C. M. Conway, Pisoni, & Kronenberger (2009). This hypothesis asserts that musical training leads to enhanced working memory abilities and to a general enhancement of sensitivity to the statistical relationships of elements within a sequential input. It asserts that because sound is inherently a temporal and sequential signal, experience with sound may help bootstrap the development of general cognitive abilities related to representing temporal or sequential patterns. This association is based on two lines of findings. First, individuals (even with no musical background) do best on sequencing tasks (e.g., artificial grammar learning, Reber, 1967) when the sense of hearing, rather than vision, can be used (e.g., C. M. Conway & Christiansen, 2005). Second, deaf children have difficulties in tasks that involve learning and manipulation of serial order information (Marschark, 2006). The scaffolding hypothesis suggests that sequence learning abilities may rely on a “modality-neutral” mechanism in addition to a modality-specific one (C. M. Conway et al., 2009).
And thus, because hearing is the primary gateway for perceiving high-level sequential patterns of stimuli, the development of sequence learning mechanisms would be delayed when this type of input is unavailable (among deaf) and enhanced when it is extensively practiced (among musicians). Consistent with this hypothesis, Patel (2003) and Tillmann (2012) suggested that at least partially shared resources are dedicated to processing music, syntax, and semantics in language and probably other mental operations, such as sequencing actions. Patel (2011) proposed that music training can enhance plasticity in speech processing networks, and Tillmann (2012) further argued that musicians’ expertise with musical structures may make them expert on temporal integration processes in other domains as well.

An alternative account to musicians’ working memory advantage is a selection bias. Namely, individuals drawn to music may be individuals with initially higher working memory skills, which may boost their musical skills. Two observations are in line with this interpretation. First, we previously studied dyslexic musicians (Weiss, Granot, & Ahissar, 2014). These musicians had the same amount of musical training as their nondyslexic peers. Yet, their auditory working memory skills (verbal and nonverbal) were poorer. Namely, musical education does not necessarily enhance working memory skills and definitely does not enhance them to a similar degree. Second, in the current study, we found that although sequential visual discrimination thresholds were better in musicians, these thresholds were not correlated with the amount of musicians’ formal musical training. These observations challenge the account of musical training as a cause, and yet they do not refute it, leaving the causality issue open.

In the current study, we also found that musicians’ performance was superior in the syllable-span task, in line with previous literature (Brandler & Rammsayer, 2003; Chan et al., 1998; Helmbold, Rammsayer, & Altenmüller, 2005; Ho et al., 2003; Jakobson et al., 2008; Kilgour et al., 2000; Kraus, 2012). But we found no group difference in Digit-Span (Table 1). The latter is probably more prone to strategies that promote performance and hence perhaps underestimates musicians’ verbal memory advantage. An opposite pattern was previously found in blind individuals, whose Digit-Span score was substantially superior to that of their sighted peers whereas their phonological memory, measured with pseudo–word repetition, was only mildly better than their peers’ (Rokem & Ahissar, 2009). Although for musicians there is no specific advantage in practicing Digit-Span, it may be (at least used to be) ecologically relevant for blind individuals, who reported the use of strategies in this test.

**No general transfer to spatial vision**

Previous studies suggested that musicians’ rich experience with reading musical notes leads to their better performance on spatial vision tasks (e.g., Brochard et al., 2004). Musical notations map temporal and spectral aspects of sounds to the horizontal and vertical visual dimensions, respectively. Reading musical notation has been associated with the functioning of the parietal lobes (Schön, Anton, Roth, & Besson, 2002; Stewart et al., 2003). In line with these findings, it was reported that the volume of gray matter in various brain regions, including the superior parietal areas, is correlated with proficiency in music (i.e., the largest volume was reported for professional musicians, intermediate volume in amateur musicians, and smallest in nonmusicians; Gaser & Schlaug, 2003). Studies in the general population have shown that parietal areas play an important role in integrating multimodal sensory information (i.e., Bushara, Weeks, & Ishii, 1999; Hutchinson, Uncapher, & Wagner, 2009; Praamstra, Boutsen, & Humphreys, 2005). Moreover, they are activated during sequential spatial frequency discrimination tasks (Greenlee, Magnussen, & Reinvang, 2000). These findings suggest that musicians’ enhanced performance on the sequential spatial frequency discrimination task could be related to enhanced activity in parietal areas.

**Conclusions**

The present study examined musicians’ spatial frequency discrimination by administering assessments that tested *sequential* and *simultaneous* comparisons. The results showed that when matched for general reasoning abilities, musicians are superior to nonmusicians in the *sequential* condition. Thus, musicians are not generally superior in spatial–visual tasks. They seem to have an improved working memory component, which may also be involved in visual comparisons. In line with these observations, nonmusicians’ verbal memory scores were correlated with their sequential spatial frequency thresholds and not with their simultaneous frequency discrimination thresholds. This observation further indicates that choice of the psychophysical procedure for assessing perceptual skills may affect the neural mechanisms that pose the bottlenecks to the measured performance. Thus, thresholds measured with a temporal forced choice procedure may be limited by central working memory mechanisms rather than by sensory bottlenecks.

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