Temporal Information Processing in Musicians and Nonmusicians

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the present study was designed to examine the general notion that temporal information processing is more accurate in musicians than in nonmusicians. For this purpose, 36 academically trained musicians and 36 nonmusicians performed seven different auditory temporal tasks. Superior temporal acuity for musicians compared to nonmusicians was shown for auditory fusion, rhythm perception, and three temporal discrimination tasks. The two groups did not differ, however, in terms of their performance on two tasks of temporal generalization. Musicians' superior performance appeared to be limited to aspects of timing which are considered to be automatically and immediately derived from online perceptual processing of temporal information. Unlike immediate online processing of temporal information, temporal generalizations, which involve a reference memory of sorts, seemed not to be influenced by extensive music training.

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Although there is no clear agreement on a definition of music ability (cf., Bentley, 1966; Colwell, 1970; Lundin, 1967; Radocy & Boyle, 1979; Shuter-Dyson, 1999), numerous aptitude tests in music are based on various aspects of auditory performance and tonal and rhythmic concepts (e.g., Drake, 1954; Kwalwasser, 1953; Seashore, 1919). For example, the "Seashore Measures of Musical Talents" (Seashore, Lewis, & Saetveit, 1956) were intended to assess music aptitude by means of different tests referred to as Sense of Pitch, Sense of Intensity, Timbre, Tonal Memory, Sense of Time, and Sense of Rhythm. According to music aptitude tests, better performance on temporal information processing, as reflected by temporal discrimination or rhythm perception tasks, appears to be positively related to higher music aptitude. The assessment of music ability by means of music aptitude tests, however, represents a highly disputed issue, since construct validity of such tests has been questioned by many researchers (e.g., Anastasi, 1961; Henson & Wyke, 1982; Motte-Haber, 1996; Winner & Martino, 1993). It is doubtful that measurement of a small number of isolated sensorimotor abilities does justice to the complexity of music abilities (Haroutounian, 2000; Henson & Wyke, 1982; Rainbow, 1965; Sloboda, 1985).

The notion of a positive functional relationship between music ability and performance on temporal information processing is also supported by the finding that musicians performed significantly better than nonmusicians in detecting small time changes embedded in regular auditory sequences (Jones & Yee, 1997; Yee, Holleran, & Jones, 1994), although these results may apply only to specific aspects of temporal judgments. For example, when musicians were asked to judge whether after a regular sequence of five stimuli at 250-ms intervals the last of these sequential auditory or tactile stimuli occurred 25 ms later or earlier than expected (e.g., after a 225- or a 275-ms interval), musicians did not perform better than nonmusicians (Lim, Bradshaw, Nicholls, Altenmüller, 2003).

It is still under discussion to what extent time perception in musicians depends on sensorimotor co-representations, since it is known that musicians establish tight neuronal coupling of auditory, somatosensory, and motor brain areas (Bangert & Altenmüller, 2003). In music performance, musicians frequently attain extremely precise timing control. This has been demonstrated in several contexts. Wagner (1971) assessed the rhythmical precision of playing a C-major scale in professional pianists. He found at a required speed of about six key-strokes per second a standard deviation of 6 to 10 ms in a group of 11 pianists when calculating the temporal deviations of 30 subsequent key-strokes. An even higher degree of regularity of cyclic trill movements in a pianist was found by Moore (1992) using

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MIDI-technology and electromyography. He showed the temporal deviation between two trill cycles to be less than 3 ms. When amateur drummers are compared with professional drummers of different degrees of drumming expertise, timing regularity of subsequent beats were clearly related to the cumulative practice time of the respective players (Trappe, Katzenberger, & Altenmüller, 1998). The advantage of professional musicians in timing tasks, requiring sensorimotor integration is also documented in a less specific context. Musically trained individuals generally seem to show smaller mean negative asynchronies than untrained individuals when asked to tap in beat with a metronome (Aschersleben, 2002).

The present study was designed to further investigate the notion that temporal information processing of a purely perceptual nature, that is, low-level timing processes that do not involve a motor component, is more accurate in musicians than in nonmusicians. Our approach was based on a comparison of timing performance between academically trained musicians, who received music training for at least 14 years, and participants without any music experience, who were matched with regard to age, gender, and level of education. For this purpose, we employed a set of seven basic timing tasks that do not involve higher-level cognitive abilities for processing of rhythm, tempo, and timing.

Since temporal discrimination is easier with auditory stimuli than with visual ones (e.g., Grondin, 2001; Ulrich, Nitschke, & Rammsayer, in press), only auditory temporal tasks were applied. As psychophysical indicators of individual temporal resolution, performance measures for auditory fusion, rhythm perception, and interval timing in the range of seconds and milliseconds were obtained.

Auditory fusion refers to the size of the temporal interval between two events that is required for them to be perceived as two separate events rather than fused as one event. Thus, auditory fusion thresholds represent a psychophysical indicator of temporal resolving power for central sensory information processing (McCroskey & Kasten, 1980; Robin & Royer, 1987).

The major focus of *rhythm perception* is on discrimination of serial temporal patterns (ten Hoopen et al., 1995). Commonly, in a rhythm perception task, a participant is presented with a click pattern, devoid of any pitch, timbre, or dynamic variations to avoid possible confounding influences on perceived rhythm. The participant's task is to detect a deviation from regular, periodic click-to-click intervals.

For assessment of performance on *interval timing,* three temporal discrimination and two temporal generalization tasks were used. In a typical *temporal discrimination task,* a participant is presented with two intervals and his/her task is to decide which of the two intervals was longer. There are two types of stimuli used in temporal discrimination studies. One type is the filled interval and the other type is the empty interval (cf., Grondin, 2001). In filled auditory intervals, for example, a tone is presented continuously throughout the interval, whereas in empty auditory intervals only the onset and the offset of the interval are marked by clicks or brief tone bursts. The common finding of better timing performance with filled than with empty auditory intervals (e.g., Abel, 1972a, 1972b; Craig, 1973; Rammsayer & Lima, 1991; Rammsayer & Skrandies, 1998) may suggest different timing mechanisms involved in the processing of filled and empty intervals (Craig, 1973).

Furthermore, timing of brief intervals in the range of milliseconds appears to be dependent on sensory processes beyond cognitive control (Münsterberg, 1889; Michon, 1985; Rammsayer, 1999; Rammsayer & Lima, 1991), while temporal processing of longer intervals is likely to be cognitively mediated (Brown, 1997; Fortin & Breton, 1995; Rammsayer & Lima, 1991). Based on these considerations, three temporal discrimination tasks were employed: one task with filled and one task with empty intervals, both with a 50-ms standard duration, and one task with filled intervals with a 1,000-ms standard duration.

In addition to the temporal discrimination tasks, two *temporal generalization tasks* were used with standard durations of 75 and 1,000 ms, respectively. Unlike temporal discrimination, temporal generalization relies on timing processes as well as a reference memory of sorts (Church, 1984; Church & Gibbon, 1982; McCormack, Brown, Maylor, Richardson, & Darby, 2002). This is because, with the latter task, participants are presented with a reference duration during a preexposure phase and are required to judge whether the durations presented during the test phase were the same as the reference duration that they have encountered earlier.

Based on the notion that distinct processes may be involved in temporal processing of intervals in the sub-second and second range, we applied both brief and long intervals. The brief and long standard durations of the interval timing tasks were selected because the hypothetical shift from one timing mechanism to the other may be found at an interval duration somewhere between 100 and 500 ms (Abel, 1972a; Buonomano & Merzenich, 1995; Michon, 1985; Münsterberg, 1889). Although the nature of the study was mainly explorative, one underlying hypothesis was that musicians would perform better on both types of tasks. While perception of brief intervals is a prerequisite for rhythmic precision, perception of long intervals is necessary for keeping the tempo.

Eventually, when participants are asked to compare time intervals, many of them adopt a counting strategy. Since explicit counting becomes a useful timing strategy for intervals longer than approximately 1,200 ms (Grondin, Meilleur-Wells, & Lachance, 1999), the "long" standard duration was chosen not to exceed this critical value.

Method

Participants

Two groups of participants, musicians and nonmusicians, participated in the study. The musician group included 21 female musicians (mean age: 27.9 ± 7.4 years) and 15 male musicians (mean age: 30.4 ± 6.4 years). All participants of the musician group were either graduate students at the Hochschule für Musik und Theater, Hannover, Germany, with music as their main subject, or professional musicians who already possessed an academic degree in music. All musicians had music training as instrumentalists for at least 14 years. The nonmusician group included 21 female nonmusicians (mean age: 24.9 ± 5.6 years) and 15 male nonmusicians (mean age: 28.7 ± 4.8 years). All nonmusicians were students at the University of Göttingen or had already obtained an academic degree (psychology, law, physics, engineering, social sciences) and reported that they had never played any music instrument, nor were they especially interested in music. Thus, none of the nonmusicians was occupied with music to a greater extent than occasionally listening to music. The level of education was matched between the two groups insofar as that both musicians and nonmusicians possessed the German Abitur, a high school degree required to enroll at German universities, and that both groups were comparable in terms of their level of university training.

Temporal Discrimination Tasks

Stimuli. Filled intervals were white-noise bursts presented binaurally through headphones (Vivanco SR85) at an intensity of 67 dB SPL. The empty intervals were marked by onset and offset clicks 3 ms in duration, with an intensity of 88 dB.

Procedure. Because interval timing may be influenced by type of interval (filled vs. empty) and base duration, the duration discrimination task consisted of one block of filled and one block of empty intervals with a base duration of 50 ms each, as well as one block of filled intervals with a base duration of 1,000 ms.

The order of blocks was counterbalanced across participants. Each block consisted of 64 trials, and each trial consisted of one standard interval and one comparison interval. The duration of the comparison interval varied according to an adaptive rule (Kaernbach, 1991) to estimate $x.25$ and $x.75$ of the individual psychometric function, that is, the two comparison intervals at which the response "longer" was given with a probability of .25 and .75, respectively. In each experimental block, one series of 32 trials converging to $x.75$ and one series of 32 trials converging to $x.25$ were presented. Within each series, the order of presentation for the standard interval and the comparison interval was randomized and balanced, with each interval being presented first in 50% of the trials. Trials from both series were randomly interleaved within a block.

On each trial, the two intervals were presented with an interstimulus interval (ISI) of 900 ms. The participant's task was to decide which of the two intervals was longer and to indicate his or her decision by pressing one of two designated response keys. After each response, visual feedback ("+", i.e., correct; "−", i.e., incorrect) was displayed on the computer screen for 1.5 sec. The next trial started 900 ms after the feedback.

As an indicator of discrimination performance, half the interquartile ranges [(75%-threshold value − 25%-threshold value)/2], representing the difference limen, *DL* (Luce & Galanter, 1963), was determined for each duration discrimination task. With this measure, better performance on duration discrimination is indicated by smaller values of *DL*.

Temporal Generalization Tasks

Stimuli. The stimuli were sine wave tones presented through headphones at an intensity of 67 dB SPL. The standard duration of the long intervals was 1,000 ms and the nonstandard durations were 700, 800, 900, 1,100, 1,200, and 1,300 ms. The standard duration of the short intervals was 75 ms and the nonstandard durations were 42, 53, 64, 86, 97, and 108 ms.

Procedure. Performance on temporal generalization was assessed separately for intervals in the range of milliseconds and seconds. Order of the two temporal generalization tasks was randomized and balanced across participants. Participants were required to identify the standard stimulus among the six nonstandard stimuli. In the first part of the experiment, participants were instructed to memorize the standard stimulus duration. For this purpose, the standard interval was presented five times accompanied by the display "This is the standard duration." Then participants were asked to start the test.

The test task consisted of eight blocks. Within each block, the standard duration was presented twice, while each of the six nonstandard intervals was presented once. All duration stimuli were presented in randomized order.

On each test trial, one duration stimulus was presented. Participants were instructed to decide whether or not the presented stimulus was of the same duration as the standard stimulus stored in memory. Immediately after presentation of a stimulus, the display "Was this the standard duration?" appeared on the screen, requesting the participant to respond by pressing one of two designated response keys. Each response was followed by visual feedback. The next trial started 900 ms after the feedback.

As a quantitative measure of performance on temporal generalization an individual index of response dispersion was determined (McCormack, Brown, Maylor, Darby, & Green, 1999). For this purpose, the proportion of total "yes"-responses to the standard duration and the two nonstandard durations immediately adjacent (e.g., 900, 1,000, and 1,100 ms) was determined.

This measure would approach 1.0 if all "yes"-responses were clustered closely around the standard duration.

Rhythm Perception Task

Stimuli. The stimuli consisted of 3-ms clicks presented binaurally through headphones at an intensity of 88 dB.

Procedure. Participants were presented with auditory rhythmic patterns, each consisting of a sequence of six 3-ms clicks marking five beat-to-beat intervals. Four of these intervals were of a constant duration of 150 ms, while one interval was variable (150 ms + x). The magnitude of x changed from trial to trial depending on the participant's previous response according to the weighted up-down procedure (Kaernbach, 1991) which converged on a probability of hits of .75. Correct responding resulted in a decrease of x and incorrect responses made the task easier by increasing the value of x. Thus, the weighted up-down procedure was used to determine the 75% threshold as an indicator of performance on rhythm perception. A total of 64 experimental trials were grouped in two independent series of 32 trials each. In Series 1, the third beat-to-beat interval was the deviant interval, while in Series 2 the fourth beat-to-beat interval was the deviant interval. Trials from both series were randomly interleaved.

The participant's task was to decide whether the presented rhythmic pattern was perceived as "regular" (i.e., all beat-to-beat intervals appeared to be of the same duration) or "irregular" (i.e., one beat-to-beat interval was perceived as deviant). Participants indicated their decision by pressing one of two designated response keys. No feedback was given, as there were no perfectly isochronous ("regular") patterns presented.

Auditory Flutter Fusion (AFF) Task

Stimuli. The stimuli consisted of 25-ms noise bursts presented binaurally through headphones at an intensity of 88 dB.

Procedure. AFF threshold estimation consisted of 12 trials, and each trial consisted of two noise bursts separated by a variable ISI ranging from 1 to 40 ms. After each trial, the participant's task was to indicate by pressing one of two designated response keys whether he or she perceived the two successive noise bursts as one sound or two separate sounds. The ISI was changed using an adaptive rule based on the Best PEST procedure (Pentland, 1980) to estimate the 75% fusion threshold. To enhance reliability of measurement, two AFF-threshold estimates were obtained for each participant. Thus, final individual threshold values represented the mean across both measurements.

Time Course of the Experiment

All experiments were carried out in a sound-attenuated room. The experiment was initiated by the three duration discrimination tasks followed by the two temporal generalization tasks, rhythm perception, and the AFF task. The experimental trials of all temporal tasks were preceded by practice trials to ensure that the participants understood the instructions and to familiarize them with the stimuli.

Results

Table 1 reports mean performance and standard error of the means on the seven temporal tasks for musicians and nonmusicians. As can also be seen from Table 1, t tests revealed that performance on all three temporal discrimination tasks, rhythm perception, and auditory fusion was significantly better for the musician than for the nonmusician group. All these differences were also reflected by effect size estimates d. Significant differences between both groups were shown neither for temporal generalization with a standard stimulus duration of 75 ms nor for temporal generalization with a standard stimulus duration of 1,000 ms.

Additional correlational analyses suggested different relations among aspects of temporal information

TABLE 1. Mean performance (± *S.E.M.*) on seven different temporal tasks for musicians and nonmusicians. Also given are *t* values and effect size estimates (*d*) for the differences obtained.

Temporal task	Indicator of performance	Musicians *M*	Musicians *S.E.M.*	Nonmusicians *M*	Nonmusicians *S.E.M.*	*t*	*d*
TD1	DL [ms]	7.6	.46	9.2	.55	−2.30*	.54
TD2	DL [ms]	13.7	1.08	19.5	1.80	−2.74**	.65
TD3	DL [ms]	105.6	4.71	152.4	16.85	−2.69**	.64
TG1	Response dispersion	.8	.02	.8	.03	1.59	−.37
TG2	Response dispersion	.7	.02	.8	.02	−1.33	.31
RP	75% threshold [ms]	39.9	2.11	51.9	3.55	-2.91**	.68
AFF	75% threshold [ms]	4.3	.35	11.3	1.61	−4.29***	1.01

Note. TD1: temporal discrimination of filled intervals, standard = 50 ms; TD2: temporal discrimination of empty intervals, standard = 50 ms; TD3: temporal discrimination of filled intervals, standard = 1,000 ms; TG1: temporal generalization, standard = 75 ms; TG2: = temporal generalization, standard = 1,000 ms; RP: rhythm perception; AFF: auditory flutter fusion; DL = difference limen.
* $p < .05$. ** $p < .01$. *** $p < .001$.

processing for musicians and nonmusicians (see Table 2). It should be noted that the index of response dispersion obtained with the temporal generalization tasks is positively related to performance, that is, better performance is indicated by higher values of response dispersion, while the other psychophysical measures based on threshold estimates are negatively associated with temporal performance, that is, better performance is reflected by lower threshold values and DL. Therefore, to enhance clarity of data presentation, the sign (+ or −) of the correlation coefficients presented in Table 2 has been adjusted in a way that positive correlation coefficients indicate a positive covariation of performance in respective temporal tasks. In the nonmusician group, the matrix of intercorrelations showed a larger amount of significantly positive coefficients than in the musicians' group indicating a stronger functional relationship among the different temporal tasks.

This pattern of results may be indicative of differences in the dimensional structure of temporal information processing between both groups. To further analyze the dimensional structure of temporal information processing, principal components analyses were performed separately for the musician and the nonmusician samples. It is important to note, however, that this analysis was highly exploratory in nature as the sample sizes were rather small and correlations among temporal tasks were relatively low in the musicians' group. The scree criterion (Cattell, 1966; Cattell & Vogelmann, 1977) was applied to the extraction of factors. While in the musician group, the scree test supported a two-factor solution, it favored a one-factor solution in the nonmusician group. Results of the principal components analysis for both groups are presented in Table 3.

TABLE 2. Intercorrelations among performances on the seven temporal tasks in the musician and nonmusician samples.

	TD1	TD2	TD3	TG1	TG2	RP
Musicians						
TD2	.46**					
TD3	.19	.40*				
TG1	.13	.08	.34*			
TG2	.19	.16	.15	.17		
RP	.03	.11	.24	.19	.14	
AFF	.07	.05	.23	.21	.18	.19
Nonmusicians						
TD2	.49**					
TD3	.41*	.61***				
TG1	.24	.57***	.29			
TG2	.09	.37*	.43**	.24		
RP	.30	.43**	.23	.12	.04	
AFF	.26	.60***	.47**	.38*	.43**	.39*

* $p < .05$. ** $p < .01$. *** $p < .001$ (two-tailed).

TABLE 3. Results of the principal components analysis for the musician and nonmusician groups: Factor loadings, eigenvalue, and explained variance.

	Musicians Factor 1	Musicians Factor 2	Nonmusicians Factor 1
TD1	.55	−.49	.58
TD2	.74	−.20	.89
TD3	.75	.12	.76
TG1	.36	.69	.61
TG2	.50	−.03	.53
RP	.36	.57	.49
AFF	−.19	.61	.77
Eigenvalue	1.96	1.46	3.20
Explained variance %	27.99	20.90	45.70

In the musician group, two unrotated, orthogonal factors accounted for 48.89% of total variance. The first factor was clearly associated with temporal discrimination in the range of seconds and milliseconds, as it was marked by high positive loadings on all three temporal discrimination tasks. The second factor was characterized by AFF, rhythm perception, and temporal generalization of brief intervals in the millisecond range.

Based on the scree test, in the nonmusician group, principal components analysis yielded a one-factor solution (eigenvalue = 3.20) that accounted for 45.70% of total variance. As shown in Table 3, all seven temporal tasks exhibited substantial positive loadings on this factor. Apart from rhythm perception, all loadings were greater than .50.

Discussion

The major goal of the present study was to examine the general notion that temporal information processing is more accurate in musicians than in nonmusicians. For this purpose, timing performance on seven different auditory temporal tasks was compared in 36 academically trained musicians and 36 controls without music experience. Superior temporal acuity for musicians compared to nonmusicians was shown for auditory fusion, rhythm perception, temporal discrimination of very brief filled and empty intervals in the range of milliseconds, and temporal discrimination of filled intervals in the range of seconds. Group differences were not observed, however, for temporal generalization with 75 and 1,000 ms standard durations.

The emergence of a very strong single component in the nonmusician group may be interpreted as evidence for a prominent source of shared variance among various aspects of temporal information processing. Since perceptual timing tasks require processing changes in information over time, several authors (e.g., Burle & Bonnet, 1997, 1999; Rammsayer & Brandler, 2002; Surwillo, 1968) put forward the idea that a general internal timing mechanism in the brain is responsible for various aspects of temporal information processing such as rhythm perception or interval timing. More specifically, performance on interval timing is often explained by the general assumption of a hypothetical internal clock based on neural counting (e.g., Creelman, 1962; Gibbon, 1977; Rammsayer & Ulrich, 2001; Treisman, Faulkner, Naish, & Brogan, 1990). As opposed to the nonmusicians, for the musician group, at least two independent components were found. Both the differential dimensional structure of temporal processing skills in musicians and nonmusicians as well as the apparent lack of a reliable correlational relationship among the seven temporal tasks in the musician group argue against the notion of a unitary timing mechanisms underlying perceptual timing. The correlational results of the musician group rather suggest the existence of task-specific timing mechanisms, most of which can be influenced by music training as indicated by the musicians' superior performance. The positive manifold among the seven temporal tasks observed for the nonmusician group, may imply that, under untrained conditions, functional independence of different timing mechanisms cannot be detected. Only after extensive "temporal training," when the respective timing mechanisms operate at an optimum level, does a dissociation of task-specific timing mechanisms become evident. Within the framework of the present study, task-specific optimum timing performance can be considered a by-product of early music training.

Furthermore, there are some important functional differences between temporal discrimination and generalization that need to be addressed. In a typical temporal discrimination task, the standard and a comparison interval are presented on each trial. In order to decide which interval was longer, the internal representations of both the standard and the comparison interval need to be compared immediately at the end of each trial. With the temporal generalization task, however, participants are presented a standard duration during an initial learning phase. Then, in the subsequent test phase, they receive a series of comparison stimulus durations shorter than, longer than, or equal to the standard duration. The participants' task is to indicate whether or not the just-presented comparison duration matched the standard duration. To perform this task, an internal representation of the standard duration has to be stored in reference or long-term memory while the just-presented duration of the comparison is stored in short-term or working memory (Church, 1984; McCormack et al., 2002). In order to decide whether or not the just-presented duration matched the standard duration, the participant evaluates the difference between the just-presented duration and the temporal memory of the standard duration.

From this perspective, musicians' superior performance on perceptual temporal tasks, that do not require reference memory processes, suggests that extensive music training may exert a positive effect on timing performance by reducing variability or noise associated with the timing process. This advantage of musicians compared to nonmusicians appears to be limited to aspects of timing performance which are considered to be automatically and immediately derived from online perceptual processing of temporal information. On the other hand, the absence of a performance difference between musicians and nonmusicians for temporal generalization tasks, which involve a reference memory of sorts, points to the conclusion that temporal judgments which cannot be derived automatically or immediately from perceptual processing are less sensitive to music training.

It should be noted, however, that professional conductors are known for their superior temporal generalization skills and stable mental representations of tempo. For example, Christoph Wagner (1974) asked the famous conductor Herbert von Karajan to rehearse twice different works of the classical music repertoire and found a remarkable constant tempo in both versions in most pieces, although there was a slight tendency to increase tempo in the second version. It has to be acknowledged that the specific training of conductors may explain their outstanding abilities concerning memorization of tempo. Similar effects of music specialization have been demonstrated recently with respect to the conductors' ability to localize sound sources in the periphery of the auditory field (Münte, Kohlmetz, Nager, & Altenmüller, 2001). In the present study, however, only musicians playing an instrument where invited to participate. Their ability to stay in tempo and to structure time not only relies on perception but also on motor executive functions. Typically, professional musicians develop a motor representation of music (Bangert & Altenmüller 2003; Haslinger et al. 2005) and may therefore need executive functions and motor patterns to deal with demanding tasks of tempo generalization. Support for our argument comes from the tapping literature, demonstrating that musicians' generally are superior in timing tasks when motor output such as tapping to a beat is required (for a review see Repp, in press). Thus, it cannot be ruled out that, in the present study, musicians would have performed better than the nonmusicians on the temporal generalization tasks if the tasks would have also comprised a distinct motor component. Furthermore, the present finding of no difference in temporal generalization between musicians and nonmusicians may also be due to the fact that this task does not measure memory for tempo of music but a more basic perceptual function.

An alternative, tentative interpretation of the lack of a difference observed with the temporal generalization task is that sensitivity to group differences might have been lower for the response-dispersion measure used in the temporal generalization tasks than for the difference limen and threshold measures used in the other tasks. While in previous studies, performed to evaluate the sensitivity of assessment, reliability coefficients were shown to range from .82 to .99 for the duration discrimination tasks (Brandler & Rammsayer, 1999; Rammsayer, 1994; Rammsayer & Brandler, 2001), the rhythm perception task (Brandler & Rammsayer, 2000), and the AFF task (Rammsayer & Brandler, 2004), to our knowledge, the reliability of temporal generalization tasks has not been evaluated yet. Thus, it cannot be ruled out that differences in procedural sensitivity could have contributed to our findings.

The overall pattern of our findings suggests that perceptual timing skills are superior in musicians, while most of their training has been in more complex performance skills. This links in well with present theories on perception-action coupling, which is best expressed in the "common-coding hypothesis" (Prinz 1990): training of precise timing in motor performance is inseparably linked to the corresponding training and improvement of auditory temporal resolution. This is the more relevant in professional musicians, since temporal precision is a fundamental characteristic of performance quality.

The musicians' superior performance in temporal discrimination tasks also fits well into concepts of neuroplastic adaptation to attentive auditory processing. The size and temporal organization of cortical representations are continually shaped by experience (Singer, 1995). Animal studies over the past 20 years have gone a long way toward explaining some of the rules of cortical plasticity. For example, it has been shown that training to perform fine-grained temporal judgments yields an expansion of the receptive field or bandwidth in the auditory modality, while requiring fine grained frequency discrimination leads to a decrease in the receptive field size of cortical neurons (Kilgard, 2001). This effect has been explained by Hebbian learning rules, whereby synapses are driven to change by temporally coherent inputs in a competitive neural network (Singer 1995). In addition, attention to the sensory input and its behavioral significance were shown to be very important in driving experience-related plasticity (Ahissar & Hochstein, 1997).

In humans, a first indication that extensive music training plastically alters auditory receptive functions was provided by Pantev et al. (1998). Equivalent current dipoles, computed from evoked magnetic fields, were obtained in response to piano tones and pure tones of equal fundamental frequency and loudness. In musicians, the responses to piano tones but not to pure tones were about 25% larger than those in nonmusicians. In a further study on violinists and trumpeters, this effect was most pronounced for tones from the musicians' own type of instrument (Pantev, Roberts, Schulz, Engelien, &

Ross, 2001). Signs of plasticity in musicians were also found with respect to the temporal organization of music. The mismatch negativity (MMN; Näätänen, 1992), a frontal negative wave in the event-related potential (ERP) which is a marker for pre-attentive processing, is elicited by temporal changes in sequences of several tones (Rüsseler, Altenmüller, Nager, Kohlmetz, & Münte, 2001). Professional musicians, unlike nonmusicians, exhibit MMN for tones that occurred early by as little as 20 ms within a series of regularly spaced tones. For stimuli anticipated by 50 ms the MMN in musicians was considerably larger than that of controls.

Source localization studies showed that the MMN arises mainly from neurons on the supratemporal plain of the temporal lobe, with additional contributions from the frontal cortex (Tiitinen et al., 1993). These findings suggest that, after years of music training, neuronal populations in the auditory cortex are shaped such that they automatically detect quite subtle changes in auditory stimulus sequences with simple or higher-order regularities. The specialization of the temporal lobe in musicians is not only reflected in functional, but also in morphological changes. Schneider and colleagues (2002) elegantly demonstrated that the superior temporal gyrus is larger in musicians and that the size of this structure corresponds well with music expertise as assessed by a test of working memory for music.

The finding of musicians' superior performance on perceptual timing tasks that do not involve long-term or reference memory provides converging evidence for the validity of traditional music aptitude tests based on various aspects of tonal and rhythmic concepts, such as sense of time and sense of rhythm (Drake, 1954; Kwalwasser, 1953; Révész, 1914; Seashore, 1919). Most interestingly, in the field of human interval timing, several studies support the notion of a common timing mechanism underlying both perception and production of temporal intervals (Ivry & Hazeltine, 1995; Keele, Pokorny, Corcos, & Ivry, 1985; Pashler, 2001; Treisman, Faulkner, & Naish, 1992). Therefore, it seems reasonable to assume that rhythm perception and extremely precise motor-timing, often observed in musicians (e.g., Aschersleben, 2002; Moore, 1992; Trappe et al., 1998; Wagner, 1971), share a common neurophysiological basis.

Finally, a major problem with most studies on the relationship between music skill and aspects of perceptual and/or cognitive performance is the fact that the influence of innate music ability can hardly be investigated independently from the effects of music training. In the present study, musicians were likely to differ from the nonmusicians in both level of music ability and intensive music training from an early age. Therefore, musicians' superiority in temporal processing may be considered a consequence of their long lasting music training as well as of their outstanding, innate music talent. Certainly, numerous studies suggest that, due to neural plasticity, music training has beneficial effects on neural mechanisms related to temporal information processing. This, however, does not necessarily rule out the possibility that the individual level of music ability represented a crucial factor for musicians' superior temporal performance compared to nonmusicians in the present study. Therefore, long-term studies would be highly desirable to answer the question of whether musicians' temporal superiority reflects an innate component of music ability rather than a consequence of early, intensive music training.

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