THE EFFECTS OF EXTENSIVE MUSICAL TRAINING ON TIME PERCEPTION REGARDING HEMISPHERIC LATERALIZATON, DIFFERENT TIME RANGES AND GENERALIZATION TO DIFFERENT MODALITIES

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Thesis Abstract

Emre Sevinç, "The Effects of Extensive Musical Training on Time Perception Regarding Hemispheric Lateralization, Different Time Ranges And Generalization To Different Modalities"

Time perception and estimation are very important aspects of human behavior. Whether these are based on a single internal clock or the result of distributed and emergent processes in the brain is still a matter of debate. The present thesis investigated the effects of lateralized presentation of auditory and tactile stimulation to assess whether time estimation is lateralized and affected by stimulus modality. Additionally, performances of both female and male trained musicians were compared to those of non-musicians to evaluate the effects of gender and training in time estimation. In an identical subject design, subjects attended a time duration comparison task for short (100 to 900 milliseconds in 50 milliseconds increments with a standard stimulus of 500 msec) and long ranges (1 to 5 seconds in 250 milliseconds increments with a standard of 3000 msec) in auditory and tactile modalities. Subjects listened to pairs of sounds either monaurally or binaurally and indicated whether the two stimuli were of equal duration. Tactile (vibratory) stimuli were applied on the top of either the right or the left hand. Stimulus pairs were presented in ascending or descending order. The results suggested a gender difference; males were more accurate in time estimation. Gender differences may be due to different corpus callosum sizes between males and females. Findings also suggested that musicians were more accurate except for the short tactile range. Better performance by musicians in both modalities suggests that time estimation in one modality can be generalized to others. Additionally, an analysis of estimation errors compared to the standard durations (percent of error) indicated that overall performance was better in the long range. There was no significant laterality effect except for long range tactile condition. Better overall performances of subjects in estimating the longer standard duration suggest that there may be different timing mechanisms in the brain, such as for long ranges which may include cognitive processes and for short ranges that are more low-level (sensory) and automatic. The present results also provide support for the view that the brain does not have a lateralized internal clock.

Tez Özeti

Emre Sevinç, “Kapsamlı Müzik Eğitiminin Hemisferik Yanallaşma, Farklı Zaman Erimleri ve Farklı Modalitelere Genelleştirilmesi Bakımından Zaman Algılamasına Etkileri”

Zaman algılaması ve kestirimi insan davranışının çok önemli bileşenlerinden olup beyindeki tek bir içsel saate mi dayandığı yoksa dağıtık süreçlerden mi kaynaklandığı halen tartışma konusudur. Bu tez zaman kestiriminin uyarım modalitesi ve hemisfer yanallığına dayalı olup olmadığını değerlendirmek için yanallaşmış işitsel ve dokunsal uyarımların etkilerini inceledi. Ek olarak, cinsiyet ve eğitimin zaman kestirimindeki etkilerini değerlendirmek için eğitimli kadın ve erkek müzisyenlerin performansı müzisyen olmayanlarla karşılaştırıldı. Özdeş bir denek tasarımında, denekler, işitsel ve dokunsal olarak kısa (standart uyaran 500 milisaniye olacak şekilde 100’den 900 milisaniyeye 50 milisaniyelik artırımlarla) ve uzun (standart uyaran 3000 milisaniye olacak şekilde 1’den 5 saniyeye 250 milisaniyelik artırımlarla) süreli aralıkları içeren süreleri karşılaştırdılar. Denekler tek kulaktan (sağ ya da sol kulak) veya çift kulaktan ses çiftlerini dinleyip bunların sürelerinin aynı olup olmadığını belirttiler. Dokunsal (titreşimsel) uyaranlar sol ya da sağ elin üst kısmına uygulandı. Uyaran çiftleri artan ve azalan dizilerde sunuldu. Sonuçlar cinsiyet farklılığı göstermedi; erkeklerin zaman kestiriminde daha hassas olduğu saptandı. Cinsiyet farklılığı erkekler ve kadınlar arasındaki corpus callosum boylarının farklılığından kaynaklanıyor olabilir. Bulgular kısa süreli dokunsal görev haricinde müzisyenlerin daha hassas olduğunu da gösterdi. Müzisyenlerin daha iyi performansı, bir modalitedeki zaman kestirim performansının başka modalitelere de

genellenebileneceğini göstermektedir. Buna ek olarak, kestirim hatalarının standart uyaran sürelerine oranlarına dayalı (hata yüzdesi) analizleri, deneklerin performanslarının uzun sürelerde daha iyi olduğunu gösterdi. Uzun süreli dokunsal görev haricinde bir yanallık etkisi gözlemlenmedi. Sonuçlar müzik eğitiminin zaman kestirim performansını da etkilediğini ve işitsel olarak gerçekleşen bu eğitimin farklı modalitelere genellenebileceğine işaret etmektedir. Deneklerin genel olarak uzun sürelerde daha iyi performans göstermeleri ise beyinde farklı mekanizmalar olduğuna, uzun süreli zaman kestirimi için bilişsel süreçleri de içeren, kısa süreler için ise daha düşük seviyeli (duyusal), otomatik süreçlere dayanan mekanizmalar olabileceğini göstermektedir. Çalışmanın sonuçları beyinde belli bir bölgeye özelleşmiş bir saat olmadığı görüşünü desteklemektedir.

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This thesis is dedicated to my mother Drita Işık Sevinç and my late grandfather Şaban Sevinç.

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CHAPTER 1

INTRODUCTION

Time estimation is one of the most important aspects of human behavior in general and human cognition in particular. Since the human brain does not seem to be equipped with a high precision clock that records time intervals and compares them with the previous ones, time for us is not an accurate and absolute measure, but always an estimation of an objective physical property.

What makes the issue even more complicated is that time is not in the same category with light, sound, physical pressure, etc., all of which can be sensed and perceived directly. We have sensory organs to detect subtle changes in terms of visual, tactile or auditory stimulation; however, there is no time-sensing organ in our body, yet time estimation and discrimination are implicit in many of the tasks humans perform daily. Without timing mechanisms it is not possible to detect the location of a sound source, produce and understand speech, make music, drive an automobile, engage in sports, sleep and wake up.

Some of the tasks described above span a very wide range of time interval estimations. For example, finding the location of a sound source takes a temporal processing in the range of microseconds (Middlebrooks & Greenhaw, 1991), whereas speech or music related timing is in the milliseconds range (Masaki, Kashioka, & Campbell, 2002). On the other hand, deciding when to make a right move in some sports, estimating how long a musical piece one has just listened to lasted, and guessing how long a speech took needs temporal processing in the range of seconds to minutes. Finally, the biological clock that regulates our circadian rhythms works in the range of approximately 24 hours (Halberg & Cornélissen, 1994; Rietveld, 1996).

Perception of Time

The diversity of the phenomena of time perception in many different tasks such as sound localization, speech production and music performance has drawn a lot of interest in research since the early days of psychophysics and cognitive science. By observing performances of humans in different areas as mentioned above, it is easy to see that humans can estimate time ranges with relative accuracy. It is clear that if we could not make such estimations this would have drastic negative effect in many daily tasks including motor-control related activities. Two of the most important questions regarding time perception can be stated as "how can humans estimate time in different ranges with relative accuracy?" and "what is the source of variability in humans' estimations of time?"

Early models of time perception tried to answer the above questions in terms of a single internal-clock hypothesis (see Grondin, 2001 for a review). It was assumed that the brain somehow had a clock mechanism such as a pacemaker-accumulator system. The pacemaker 'module' was responsible for emitting pulses which the accumulator collected, leading to perception of time. The accuracy and variability of timing were related to the clock frequency. Changes in the clock frequency would account for differences in time perception. Variability would be explainable by stochastic processes of the clock, e.g. by a Poisson process.

A similar biological timing model based on Gibbon's scalar expectancy theory proposed to explain timing in animals (Gibbon, 1977). The clock based model of Gibbon and Church comprises three main processes (Gibbon & Church, 1984), namely the clock process, memory process and decision processes. The clock process includes a pacemaker, a switch and an accumulator. As stated above, the pacemaker emits pulses according to some predefined frequency model and these are switched into the accumulator. The memory process is where the information from the accumulator is passed on to the working memory and then carried to the reference memory and the decision process. The final component, the decision process, includes a comparator which receives information from working memory and reference memory, compares them and produces a yes / no answer based on the equality of magnitude of time estimations from those memories.

This model was one of the important contributions to animal and human timing even though its main theme was to provide a pure mathematical model which would fit experimental data. Although there is current research to provide neurological plausibility for this model (Matell & Meck, 2000), its assumptions of an internal clock, and a pacemaker-accumulator place a heavy practical burden because no central clock has yet been found in the brain. Since time estimation and perception are essential to and implicit in many different tasks, it is very doubtful that a specific part of the brain is dedicated to this kind of processing.

In addition to the problems mentioned above, from an evolutionary perspective, such a model is more in line with a predefined precise design and is not compatible with the brain's redundancy for various tasks. It also does not take into account the problem of different performance in characteristics for different time range estimations which is the case for time perception and estimation in humans.

There are also other models that try to account for the experimental timing data which do not assume an internal clock. For example, Dragoi et. al., 2003, provide a two-unit artificial network and related differential equations for the dynamics of the network. This model does not assume any internal clock, multiple oscillators or any explicit time based comparison process. Although lack of such assumptions provides strong points for the model, it still suffers from neuropsychological plausibility. Even though the authors give a detailed mathematical model, they do not suggest which parts or mechanisms of the human brain their model's components would correspond to. In addition, they also suggest that at least two extra oscillators are needed for their model to be able to explain the multiple timing phenomena in which two time intervals can be independently and simultaneously timed by animals.

Fortunately these are not the only types of theories in the field of time perception and estimation research. There are population clock models and simulations that, in addition to not assuming any explicit internal clock, take into account the properties of real neuron cell assemblies (Buonomano, 2005; Buonomano & Karmakar, 2002; Eagleman, et al., 2005). In this type of models, information related to time is not explicitly stored or "counted" in the central nervous system, but emerges as the "product" of the interaction of neurons. Such models are supported by interval timing experiments in the range of milliseconds. Because they do not suppose a centralized clock-like mechanism, and are based on biologically plausible neural simulations, they are more compatible with the current view of brain anatomy and functionality. Since this modeling approach is rather generic in terms of neurons, it may account for the diffuse system of different brain structures that are related to timing such as basal ganglia, cerebellum, supplementary motor area, striatum, dorsolateral prefrontal cortex and parietal cortex.

Hemispheric Communication, Lateralization and Learning of Temporal Processing

The human brain is comprised of two hemispheres which are mainly connected by the corpus callosum, a large tract of nerve fibers. Even though both hemispheres seem to be symmetrical to a first approximation, there are functional and anatomical asymmetries (Hellige, 2001). For example, most human brains have a wider frontal region in the right hemisphere whereas the frontal part of the left hemisphere is narrower and its rear part, the occipital region, is slightly wider (Hellige, 2001). This anatomical asymmetry of cerebral hemispheres is sometimes called the "counterclockwise torque" as if the brain was subjected to an angular force in the counterclockwise direction. Another anatomical asymmetry is related to the Sylvian fissure (lateral fissure) which is a boundary mark above the temporal lobe and between the frontal and parietal lobes. Generally the Sylvian fissure is longer and straighter in the left hemisphere and a bit shorter and more curved at its posterior tip in the right hemisphere (Hellige, 2001).

In addition to the anatomical asymmetries described above, there are also functional asymmetries in the brain. For example, areas related to speech production and understanding, such as Broca's and Wernicke's areas, are found in the left cerebral hemisphere of the brain (Hellige, 2001).

Hemispheric communication and lateralization add to the complexity of psychological time perception. Presently, there is no consistent model which accounts for different temporal processing data. Traditionally, it is strongly believed that the left hemisphere has an advantage in rapid temporal processing, specifically in the range of milliseconds because of the linguistic specialization of the left hemisphere (Elias, Bulman-Fleming, & McManus, 1999). On the other hand, there is evidence that the right hemispheric cortical networks, especially the right dorsolateral prefrontal cortex, and the right inferior prefrontal cortex receive focus for temporal processing in the millisecond to second range (Belin, et al., 2002; Rubia and Smith, 2004). In addition, a recent visual temporal processing experiment in which a split-brain patient took part reports a clear right hemisphere advantage in processing time intervals in the range of a few milliseconds (Gazzaniga, Corballis, & Funnel, 2003). In the reported work, two experiments were conducted. In one, pairs of black circles were presented simultaneously, during half of the trials both of them stayed on the computer monitor for the same amount of time and in the other half they had different durations of visibility. In the first half, both circles stayed on the screen for 200 milliseconds. In the second half, one of the circles stayed for 200 milliseconds and the other circle stayed for less than 200 ms by 24, 36, 48, 60 or 72 milliseconds for 240 trials in total (120 for each visual field). The split-brain patient was instructed to press the keys denoting “yes” if he thought that the circles stayed for the same amount of time, or press another set of keys denoting “no” if the circles stayed on the screen for different amounts of time. The result was that the subject’s right hemisphere had an advantage and better performance than the left hemisphere in duration comparisons. Results of this research were against the view that left hemisphere was solely specialized for temporal processing. As mentioned earlier, that evidence was supportive of the idea that temporal processing which is implicit in so many different cognitive tasks cannot be localized to a region within one hemisphere.

Notwithstanding the surprising evidence for right hemispheric advantage related to temporal processing, there is evidence for left hemispheric advantage in different modalities of temporal processing such as brief tactile stimuli. For example, when vibrations that lasted for 120 milliseconds and contained 6 msec. or 18 msec. gaps (in the middle of the vibration) were applied unilaterally to the hands of 30 first year university students, it was observed that there was a left hemisphere advantage: the left hemisphere's brief temporal gap detection performance was better than the right hemisphere's (Nicholls & Whelan, 1998).

Generalization of Temporal Processing and Search for Different Time Ranges

There is also the issue of generalization of temporal processing experience and how that relates to hemispheric lateralization. The neural population clock model of time perception briefly described in the previous section predicts that exercise must have an effect on temporal processing. In line with this idea, there is evidence that the human brain can generalize temporal processing to different modalities or different qualities. It has been found that practicing temporal interval discrimination tasks (in the range of hundreds of milliseconds) can generalize to different spectral auditory markers (Wright, et al., 1997). In that study, 14 subjects were trained for one hour per day for 100 msec intervals for ten days, and then their performance in a temporal interval discrimination task was measured. The task was to discriminate a temporal interval of 100 msec bounded by very short 1 Khz tones from longer intervals. It was found that the trained subjects were able to detect 100 msec intervals bounded by different frequencies of short tones; however, they were not able to generalize this to the untrained intervals such as 50, 200, or 500 msec. This study suggested that discrimination of auditory time intervals developed with a short period of training and this type of learning was specialized temporally but not spectrally.

Another study also suggested that short period of practice of interval timing improved performance and this ability generalized across different modalities, hemispheres and skin locations (Nagarajan, et al., 1998). The authors trained 22 subjects for 10 to 15 days for tactile temporal interval discrimination task. Subjects were provided with two mechanical vibration pulses to their palm (thenar eminence) that were separated by a fixed amount of time and then another pair of same modality of pulses which were separated by a longer target duration. They were asked to indicate which of the pairs was separated by the target (longer) duration. Once their temporal discrimination threshold was determined, they were trained for 900 trials everyday for 10 to 15 days. After the training, it was found that the subjects were able to do the similar discrimination task for the vibrations applied to other parts of the body such as different fingers and contralateral hands. They also showed similar performances for the durations that were defined by auditory signals. However the trained subjects were not able to generalize across different temporal intervals. These results suggest that even though similar time estimation mechanisms may exist in the brain for different sensory modalities, a central internal clock model is not adequate because it does not account for such generalizations and learning of interval timing.

Gender Differences

The question "is there a difference between genders regarding time estimation?" does not have a definitive answer. First of all the issue of brain asymmetry between genders is not a settled one. This is important because if the time estimation mechanism (or mechanisms) is distributed in the brain, then this may be affected by various asymmetries between genders.

Even though meta analyses do not provide conclusive evidence for detailed gender based brain asymmetries (Hellige, 2001), there are data which suggest that in some conditions such as auditory signal based time estimation, there are gender differences (Dolu, et al., 2004), suggesting that males are more accurate in prospective time estimation. Another study also provides evidence for better performance of males in time duration judgments (Loftus, et al., 1986). In addition, a review by Block, Hancock, and Zakay shows that there is some small but significant difference between genders in terms of prospective time estimation where subjects are previously informed that they would be making duration judgments (Block, Hancock, & Zakay, 2000).

There is also different evidence for hemispherical connectivity and corpus callosum differences between genders. For example a study by DeLacoste-Utamsig & Holloway provides evidence for larger splenium in the females (DeLacoste-Utamsig & Holloway, 1982). However another study by Jäncke and Steinmetz casts doubt on that evidence by failing to find evidence for significant gender differences in terms of corpus callosum shape and size (Jäncke & Steinmetz, 2003).

Thus it is reasonable to investigate the effect of gender in time estimation using different ranges, modalities and sides by having gender balanced experiment groups.

Using Music Experience

The previous sections provided evidence that humans can handle temporal processing tasks better if there had been some previous practice. There is also a generalization to different modalities, hemispheres and markers (intramodal differences) but not to different intervals.

Using some aspect of temporal expertise as in extensive professional music training can shed light on important aspects of temporal processing in the human brain. Since musical temporal processing is in the range of milliseconds, people who are music experts are good candidates to investigate the models and hypotheses of time perception, cross-modal interval estimation generalization, and hemispheric lateralization.

Previous studies provide data that show that even though musical abilities such as tonal processing (both low level pitch processing and high level melodic processing) and rhythmic processing are generally located in the right hemisphere for non-musicians, extensive professional musical training leads to the left hemisphere dominance for musical processing (Bever & Chiarello, 1974). These data lead to the prediction that people who are experts in temporal processing in the range of milliseconds must be able to do successful time discrimination judgments (in the range of tens of milliseconds to hundreds of milliseconds) for different modalities (e.g. auditory, tactile) and hemispheres. Another prediction is that, musical performance is related to the range of milliseconds and since, as stated in the previous section, that temporal processing practice does not generalize to different intervals, professional musicians are not expected to differ from non-musicians for temporal stimuli in the 1 second to 5 second range. There is also evidence suggesting that auditory temporal processing happens on two different timescales, 25-50 msec and 200-300 msec (Boemio, et al., 2005).

In the light of these ideas, an experimental task was designed to investigate the effects of musical training on timing mechanism and laterality. The task was to make time estimations in two different time ranges (short and long) for two modalities, tactile and auditory. To investigate the potential effects of laterality, stimuli were applied to the left side and the right side of the body.

The following were the hypotheses to be tested based on the current time perception framework using the experimental task mentioned above:

1. Professional musicians (M) will perform better in temporal discrimination tasks that are in the sub-second range compared to non-musicians (NM). This means that musician's errors are going to be smaller compared to non-musicians in the 100 msec. to 900 msec. (with 50 msec increments) range for both auditory and tactile modalities.
2. M will be able to generalize the above temporal discrimination task to different modalities such as tactile stimulation.
3. M and NM will have similar performance levels for temporal discrimination tasks in the 1 to 5 sec. range of time perception (with 250 msec increments).

CHAPTER 2

METHOD

Subjects

Two groups took part in the experiments, “musicians” (M) and “non-musicians” (NM). “Musician” meant a person who had at least seven years of musical training and one who played with an orchestra or a band. “Non-musician” meant a person who had no professional music training and did not play any musical instrument professionally or with an orchestra or a band.

Seventeen musicians and 22 non-musicians participated in the experiments. Both groups consisted of subjects who were either Boğaziçi University students or friends of the experimenter. They were either undergraduates or graduate students. The musician group consisted of 8 women and 9 men; with an average age of 24.11 years (SD = 2.95). The average years of musical experience for the group was 11 years (min. 7, max. 15 years). There were 12 guitar, 5 piano (keyboard), and 2 saxophone players in the group; some of the players were multi-instrumentalists.

The non-musician group consisted of 12 women and 10 men; with an average age of 26.77 years (SD = 2.91). Thirteen of the musicians and 18 of the non-musicians reported themselves as being right-handed. One male musician and 1 male non-musician reported themselves as being left-handed.

Stimuli

There were two types of stimuli: auditory sequences (auditory modality) and tactile sequences (tactile modality). The auditory sequences had pairs of auditory signals in two different ranges: R_1 as the sub-second range (100 msec. to 900 msec, 500 msec. as the standard stimulus) and R_2 as the supra-second range (1 to 5 seconds, 3 seconds as the standard stimulus). R_1 was the range between 100 msec. and 900 msec. The standard stimulus was 500 msec. and the difference was 50 msec. (Δ = 50 msec.); ranging from 100 msec. to 900 msec. in steps of 50 msec. This range included comparison intervals such as (500, 750), (250, 500), (850, 500), etc., each including the standard stimulus in the first or the last part in a counterbalanced order. The ordering of the intervals (either ascending or descending) was in fixed order but the direction of the sequence and the slot of the standard stimulus were randomized, such as ascending (e.g. (100, 500), (150, 500), (200, 500), (500, 250), (500, 300), (350, 500), ...,) or descending (e.g. (500, 900), (850, 500), (500, 800), (500, 750), (500, 700), (600, 500), …,). R_2 was the range between 1 sec. and 5 sec. The standard stimulus was 3 sec. and the difference was 250 msec. (Δ = 250 msec.); durations ranged from 1 to 5 seconds in steps of 250 msec. This range included intervals such as (3, 4.25), (3.25, 3), (5, 3), etc., each including the standard stimulus in the first or the last part in a counterbalanced order. The ordering of the intervals (either ascending or descending) was in fixed order but the direction of the sequence and the slot of the standard stimulus were randomized, such as ascending (e.g. (1, 3), (1.25, 3), (1.50, 3), (3, 1.75), (3, 2), (2.25, 3), ...,) or descending (e.g. (3, 5), (4.75, 3), (3, 4.50), (3, 4.25), (4, 3), (3, 3.75), …,). The tactile sequences had the same temporal characteristics as the auditory sequence described above.

The auditory signal used in the auditory sequences was a pure sinusoidal tone at a frequency of 1000 Hz, a sampling frequency of 44100 Hz and an amplitude of 75 dB (SPL) heard through circumaural headphones. This signal was produced and controlled by a PC (running MATLAB 6.5 software). A window of $\cos^2$ was applied to this sinusoidal wave at the beginning (rise time = 10 milliseconds) and the end (decay time = 10 milliseconds) so that the wave slowly faded in and faded out respectively. This method was applied so the subjects of the experiment would not experience a sudden rise and an immediate cut in the signal but rather a smooth beginning and an end. This also eliminated a possible cue because otherwise subjects could have used these sudden changes as a cue since a pure sinusoidal tone, without the $\cos^2$ window applied, produced easily audible clicks at the beginning and the end of stimulation. The sound pressure level of the signal was calibrated according to the author's ears wearing circumaural stereo headphones (SONY MDR XD-100). The sound signal which was produced by the PC at its highest volume was passed through a low pass filter at a frequency of 10 KHz and the output was attenuated using a programmable attenuator (Tucker Davis Technologies ZBUS System 3 PA5). The sound levels were calibrated near the tympanic membrane by using a clinical probe microphone system (ER-7C, Etymotic Research, Illinois, USA).

The tactile stimulus was created by the same PC and software described above, as an easily detectable physical vibration applied to the upper middle part of the middle finger of the hand. The middle fingers of the subjects were molded in modeling clay (Van Aken International, Rancho Cucamonga, CA) in order to prevent involuntary movement. The wave for the tactile stimulus was also purely sinusoidal at a fundamental frequency of 250 Hz and a sampling frequency of 5000 Hz. Before the start of the experiment the subjective tactile vibration threshold was measured using a two-interval forced-choice paradigm (using the TACLAB software) as described in (Güçlü & Bolanowski, 2005), and during the experiments the signal with an amplitude of 20 dB higher than the subjective tactile threshold was applied to the finger. Again a $\cos^2$ window was applied to the beginning and the end of the wave. The signal was passed through a 1 KHz filter and its output was input to the PA5 attenuator which sent the signal to the amplifier (ALESIS RA 300). The resulting wave was sent to the V203 electro-dynamic shaker (Ling Dynamic Systems Ltd., Royston, Herts, UK). The sound of the vibrator machine was masked by white noise provided through the earphones. All of the responses of the subject were obtained by a custom made box that had two switches which sent the Yes / No answers to the computer. All of this setup was located at the Psychophysics Laboratory of Boğaziçi University Biomedical Engineering Institute.

Procedure

The central task in the experiments was to detect when a pair of signals were of equal duration. The method of limits was used to find the thresholds of the subjects' threshold of temporal interval discrimination.

The components described above led to 10 different permutations for musicians and non-musicians (short range auditory stimulus for left ear, right ear and both ears; short range tactile stimulus for left hand and right hand; long range auditory stimulus for left ear, right ear and both ears, long range tactile stimulus for left hand and right hand).

To counterbalance the conditions a Latin square design was used. Each subject was first randomly assigned to either auditory or tactile condition, then left or right hand was chosen (for tactile stimulus), or left, right or both ears were chosen (for auditory stimulus) and then long range or short range was chosen.

The subjects were placed in a relatively sound-isolated room in the psychophysics laboratory in Biomedical Engineering Institute. A PC equipped with required sound and vibration synthesis software was used and a set of quality and comfortable circumaural headphones that provided sound insulation was used for presenting the auditory stimuli as described above. Two ascending and two descending sequences in two different ranges R_1 and R_2 were randomized as described above, and played through the headphones to the left, right ear or both ears, or applied by the electro-mechanical shaker to the left hand or right hand. For each signal pair, there was a 1 second pause between the signals. Subjects made a forced choice (Yes / No) temporal judgment by pressing one of the predefined keys on the switch box to indicate whether the durations of both signals of the pair were equal or not. They were instructed to press the red button if they perceived the pair of signals as of different duration or the green button if they perceived them as of same duration. Subjects were given limited time (2 seconds) to make a judgment. If no response occurred during this trial, this was counted as no decision and the next trial started. The subject was motivated to make judgments in the allowed period by being instructed to state his or her answer as soon as he or she had seen the yellow LED lit up.

The above procedure was one element of a single block. The procedure was repeated until the subject produced a Yes (meaning both signals were perceived as of equal length) response and this completed one block of trial. Four blocks of trials were run with five seconds of breaks given between blocks. Each block was randomized in terms of being in ascending or descending order and care was taken to include exactly two ascending and two descending orders. Also in order to prevent subject's counting the order and number of the intervals start of each block was offset by 1 element randomly, e.g. started with 150 msec. instead of 100 msec. (ascending) or 1.25 seconds instead of 1 second.

Measuring the Responses

A typical data set from one of the experiments (e.g. ascending auditory short range signal applied to both ears or tactile short range vibration applied to right hand) looked like the following (Y for Yes: equal durations, N for no: different durations):

(100, 500)	...	(500, 250)	(500, 300)	(350, 500)	(500, 400)	(450, 500)
N	…	N	N	N	N	Y

The point for which the 'Yes' answer was given marked the approximate boundary of the subject's threshold for temporal discrimination, the closer that was to the standard stimulus the better was the accuracy of making a temporal judgment, hence a lower threshold of temporal discrimination. The arithmetic mean of the non-standard stimulus at the last 'No' answer and the one at the 'Yes' answer was taken, for the above hypothetical data set the result would be (400 + 450) / 2 = 425 msec. Then the absolute difference between this number and the standard stimulus (e.g. 500 msec.) was taken to indicate how close the subject came to the standard stimulus, in this case 500 – 425 = 75 msec. This was the absolute difference for the ascending sequence. Using the same calculations the absolute difference for descending sequence was also calculated and the average of absolute difference of ascending and the absolute difference of descending sequence gave the average absolute difference for one permutation.

To counterbalance the experimental conditions, the subjects were first assigned one of the modalities. If they were assigned to the auditory condition, the experiment was done for either the left or the right ear, or both ears stimulated for both the short and long range auditory sequences. If subjects were first assigned to the tactile condition, similarly short and long range tactile sequences were applied either to the left or the right side of the body (the middle finger) with a counterbalanced order as described earlier. This led to the following conditions for the experiment: long range left ear, long range right ear, long range both ears, long range left hand, long range right hand, short range left ear, short range right ear, short range both ears, short range left hand, and short range right hand.

CHAPTER 3

RESULTS

For every experiment conducted for musicians and non-musicians, the pair of stimuli to which they responded as “yes” by pressing the green button (meaning that they perceived the pair of signals as having equal duration) was recorded for two ascending and two descending sequences. For each sequence average of the time point for the “yes” answer and the one before that was taken (e.g. if subject decided that the pair of signals in the long ascending range, e.g. (2500, 3000), had same duration then it was calculated as (2250 + 2500) / 2 = 2375 msec.). This led to two data points for each type of sequence (two for ascending, two for descending). The average of numbers for ascending and the average of numbers for descending sequences were calculated. This calculation gave the absolute times for one subject (one for ascending and one for descending sequence). To be able to assess the error made by subjects, the absolute difference between these two numbers and the standard stimulus (3000 msec. for long range and 500 msec. for short range) were calculated. For example, if the absolute average time for an ascending sequence was calculated as 2375 msec, then the absolute difference was 3000 – 2375 = 625 msec. Finally, the average of the absolute differences for ascending sequence and the descending sequence gave the average of absolute differences for the subject.

Gender Differences

A four way analysis of variance (ANOVA) with repeated measures on two factors (Gender x Group x Side x Ascending / Descending) for long range auditory condition indicated a significant difference between male and female subjects [$F(1, 210) = 4.62$, $p = 0.03$]. Male subjects were better than female subjects in the long range auditory time estimation. There was significant difference between musicians and non-musicians [$F(1, 210) = 33.06$, $p < 0.001$]. Musicians were better than non-musicians. There was no significant difference between sides [$F(2, 210) = 0.49$, $p = 0.48$]. There was a significant difference between ascending and descending order [$F(1, 210) = 11.99$, $p < 0.001$]. The performance of subjects was better in the ascending order. There was no interaction between gender, group, side and ordering of sequences (for Gender x Group [$F(1, 210) = 0.42$, $p = 0.51$], for Gender x Side [$F(2, 210) = 1.31$, $p = 0.30$], for Group x Side [$F(2, 210) = 0.14$, $p = 0.71$], for Gender x Ascending/Descending [$F(1, 210) = 0.30$, $p = 0.60$], for Group x Ascending/Descending [$F(1, 210) = 1.31$, $p = 0.25$], for Side x Ascending/Descending [$F(1, 210) = 2.20$, $p = 0.15$], for Gender x Group x Side [$F(2, 210) = 0.32$, $p = 0.57$], for Gender x Group x Ascending/Descending [$F(1, 210) = 2.26$, $p = 0.14$], for Gender x Side x Ascending/Descending [$F(2, 210) = 0.01$, $p = 0.97$], for Group x Side x Ascending/Descending [$F(2, 210) = 0.61$, $p = 0.44$], for Gender x Group x Side x Ascending/Descending [$F(2, 210) = 0.95$, $p = 0.33$]).

The same type of test for long range tactile condition did not show a significant difference between genders [$F(1, 134) = 1.02$, $p = 0.31$]. There was significant difference between musicians and non-musicians [$F(1, 134) = 30.23$, $p < 0.001$]. Musicians were better than non-musicians. There was no significant difference between sides [$F(2, 134) = 3.9$, $p = 0.0501$]. There was a significant difference between ascending and descending order [$F(1, 134) = 21.95$, $p < 0.001$]. The performance of subjects was better in the ascending order. There was no interaction between gender, group, side and ordering of sequences (for Gender x Group [$F(1, 134) = 0.05$, $p = 0.81$], for Gender x Side [$F(1, 134) = 1.03$, $p = 0.31$], for Group x Side [$F(1, 134) = 0.05$, $p = 0.82$], for Gender x Ascending/Descending [$F(1, 134) = 0.34$, $p = 0.56$], for Group x Ascending/Descending [$F(1, 134) = 0.04$, $p = 0.82$], for Side x Ascending/Descending [$F(1, 134) = 0.26$, $p = 0.61$], for Gender x Group x Side [$F(1, 134) = 0.99$, $p = 0.32$], for Gender x Group x Ascending/Descending [$F(1, 134) = 0.55$, $p = 0.46$], for Gender x Side x Ascending/Descending [$F(1, 134) = 0.15$, $p = 0.67$], for Group x Side x Ascending/Descending [$F(1, 134) = 0.25$, $p = 0.61$], for Gender x Group x Side x Ascending/Descending [$F(1, 134) = 0.72$, $p = 0.39$]).

The same type of test for short range auditory condition indicated a significant difference between genders [$F(1, 214) = 10.46$, $p < 0.01$]. Males were better than females in the short range auditory time estimation task. There was significant difference between musicians and non-musicians [$F(1, 214) = 14.61$, $p < 0.001$]. Musicians were better than non-musicians. There was no significant difference between sides [$F(2, 214) = 0.01$, $p = 0.97$]. There was a significant difference between ascending and descending order [$F(2, 214) = 26.88$, $p < 0.001$]. The performance of subjects was better in the ascending order. There was no interaction between gender, group, side and ordering of sequences (for Gender x Group [$F(1, 214) = 0.18$, $p = 0.67$], for Gender x Side [$F(2, 214) = 1.98$, $p = 0.30$], for Group x Side [$F(2, 214) = 0.01$, $p = 0.92$], for Gender x Ascending/Descending [$F(1, 214) = 0.50$, $p = 0.47$], for Group x Ascending/Descending [$F(1, 214) = 0.21$, $p = 0.64$], for Side x Ascending/Descending [$F(2, 214) = 0.61$, $p = 0.43$], for Gender x

Group x Side $[F(2, 214) = 0.26, p = 0.60]$, for Gender x Group x Ascending/Descending $[F(1, 214) = 0.001, p = 0.96]$, for Gender x Side x Ascending/Descending $[F(2, 214) = 0.49, p = 0.48]$, for Group x Side x Ascending/Descending $[F(2, 214) = 0.65, p = 0.42]$, for Gender x Group x Side x Ascending/Descending $[F(2, 214) = 0.86, p = 0.35]$).

The same type of test for short range tactile condition showed no significant difference between male and female subjects $[F(1, 133) = 4.35, p < 0.05]$. There was no significant difference between musicians and non-musicians $[F(1, 133) = 2.90, p = 0.09]$. There was no significant difference between sides $[F(1, 133) = 1.47, p = 0.22]$. There was a significant difference between ascending and descending order $[F(1, 133) = 17.04, p < 0.001]$. The performance of subjects was better in the ascending order. There was no interaction between gender, group, side and ordering of sequences (for Gender x Group $[F(1, 133) = 1.13, p = 0.29]$, for Gender x Side $[F(1, 133) = 2.70, p = 0.11]$, for Group x Side $[F(1, 133) = 1.21, p = 0.27]$, for Gender x Ascending/Descending $[F(1, 133) = 0.03, p = 0.85]$, for Group x Ascending/Descending $[F(1, 133) = 0.87, p = 0.35]$, for Side x Ascending/Descending $[F(1, 133) = 0.20, p = 0.65]$, for Gender x Group x Side $[F(1, 133) = 0.24, p = 0.62]$, for Gender x Group x Ascending/Descending $[F(1, 133) = 0.02, p = 0.96]$, for Gender x Side x Ascending/Descending $[F(1, 133) = 0.10, p = 0.75]$, for Group x Side x Ascending/Descending $[F(1, 133) = 0.01, p = 0.91]$, for Gender x Group x Side x Ascending/Descending $[F(1, 133) = 0.21, p = 0.64]$).

Long Range Time Estimation

Auditory Modality - Females

Fig. 1 shows the time estimations (absolute times) for the auditory long range sequence for musicians and non-musicians in the female group. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 1 summarizes the absolute time data for the long range auditory ascending and descending conditions (all numbers are in milliseconds, standard stimulus is 3000 msec).

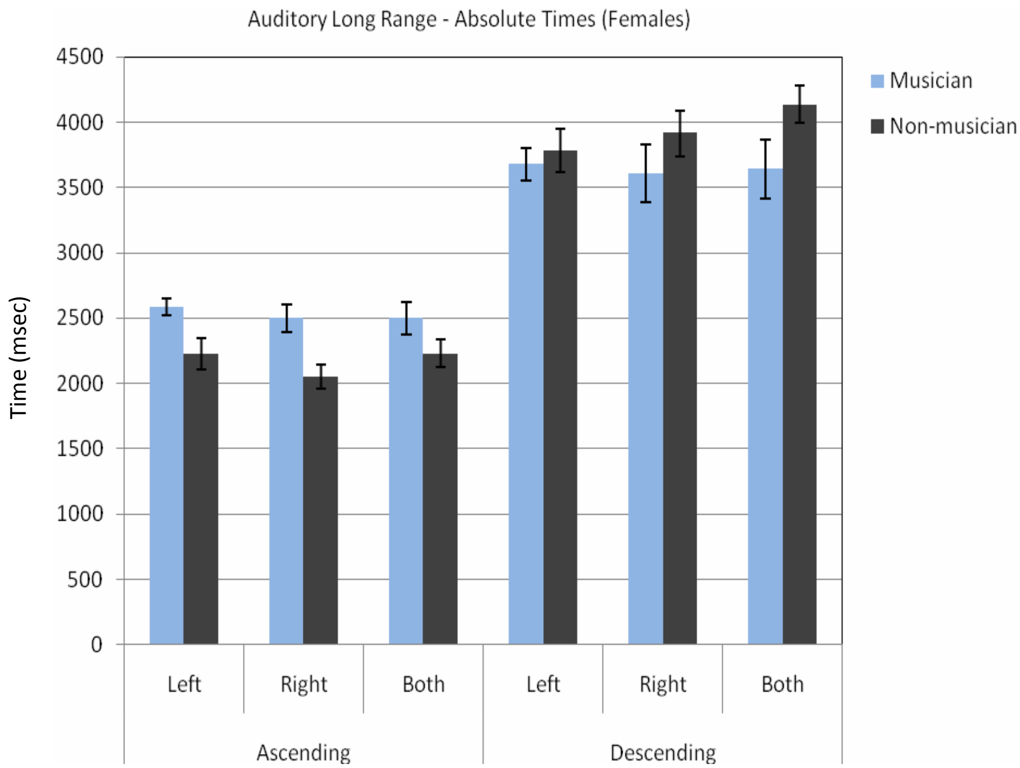

Fig. 1 The absolute average times (in milliseconds) at which female subjects decided that the tones were of equal length for ascending and descending tone sequences.

Table 1. Absolute Times for Long Range Auditory Signals in Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	2589.29	172.52	2500.00	291.24	2500.00	353.55
Non-mus.	2229.17	408.33	2052.08	326.21	2229.17	368.63
Descending						
Musician	3678.57	329.59	3609.38	631.88	3640.63	635.40
Non-mus.	3781.25	571.89	3916.67	603.81	4136.36	472.54

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for females in the auditory long range time estimation task showed no significant difference between groups [$F(1, 110) = 0.08$, $p = 0.78$]. There was no significant difference between sides [$F(2, 110) = 0.80$, $p = 0.37$]. There was a significant difference between ascending and descending orders [$F(1, 110) = 332.05$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(2, 110) = 0.15$, $p = 0.69$], for group x ascending/descending [$F(1, 110) = 1.19$, $p = 0.16$], for side x ascending/descending [$F(2, 110) = 1.49$, $p = 0.22$], for group x side x ascending/descending [$F(2, 100) = 0.58$, $p = 0.44$]).

Fig. 2 shows the absolute difference between the subjects' absolute response time and the standard stimulus for the auditory long range ascending and descending sequences. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 2 summarizes the absolute difference data for the long range auditory ascending and descending conditions (all numbers are in milliseconds).

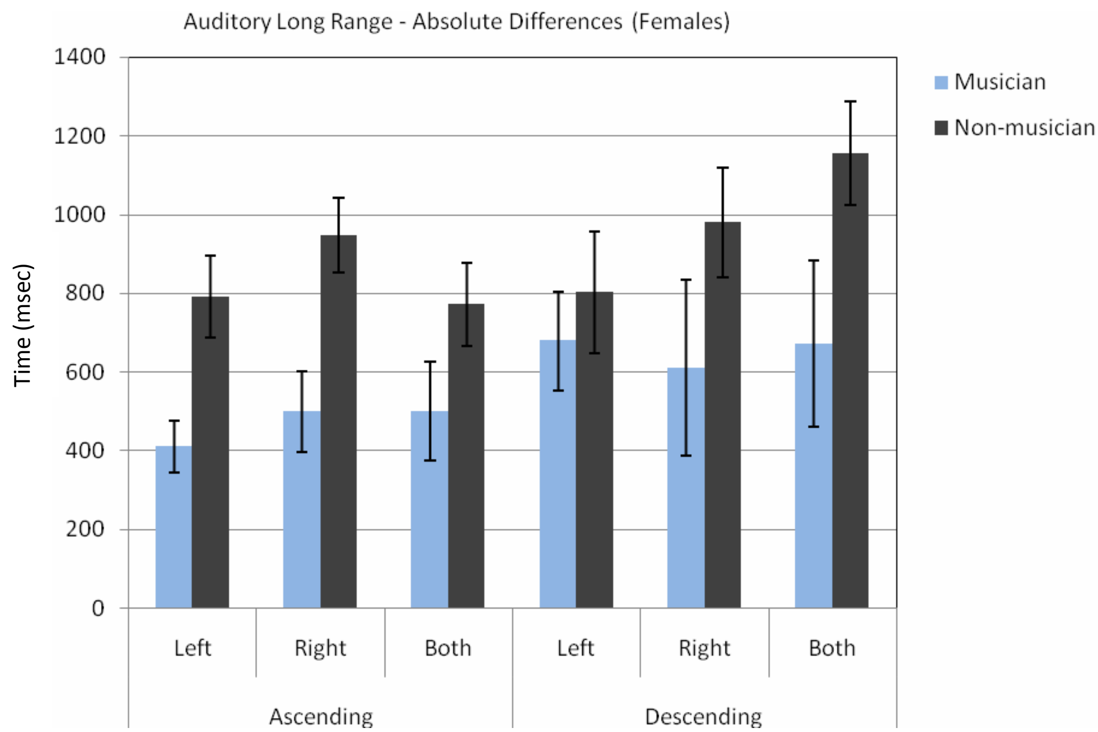

Fig. 2 The absolute difference between the female subjects' decision and the standard stimulus (3000 msec.) for ascending and descending tone sequences.

Table 2. Absolute Differences for Long Range Auditory Signals in Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	410.71	172.52	500.00	291.24	500.00	353.55
Non-mus.	791.67	362.81	947.92	326.21	770.83	368.63
Descending						
Musician	678.57	329.59	609.38	631.88	671.88	597.38
Non-mus.	802.08	539.51	979.17	326.21	1156.25	455.79

Fig. 3 shows the average of absolute differences for ascending and descending auditory long range sequences. The averages are given separately for left ear, right ear and both ears. Table 3 summarizes the average of absolute differences for ascending and descending auditory long range sequences.

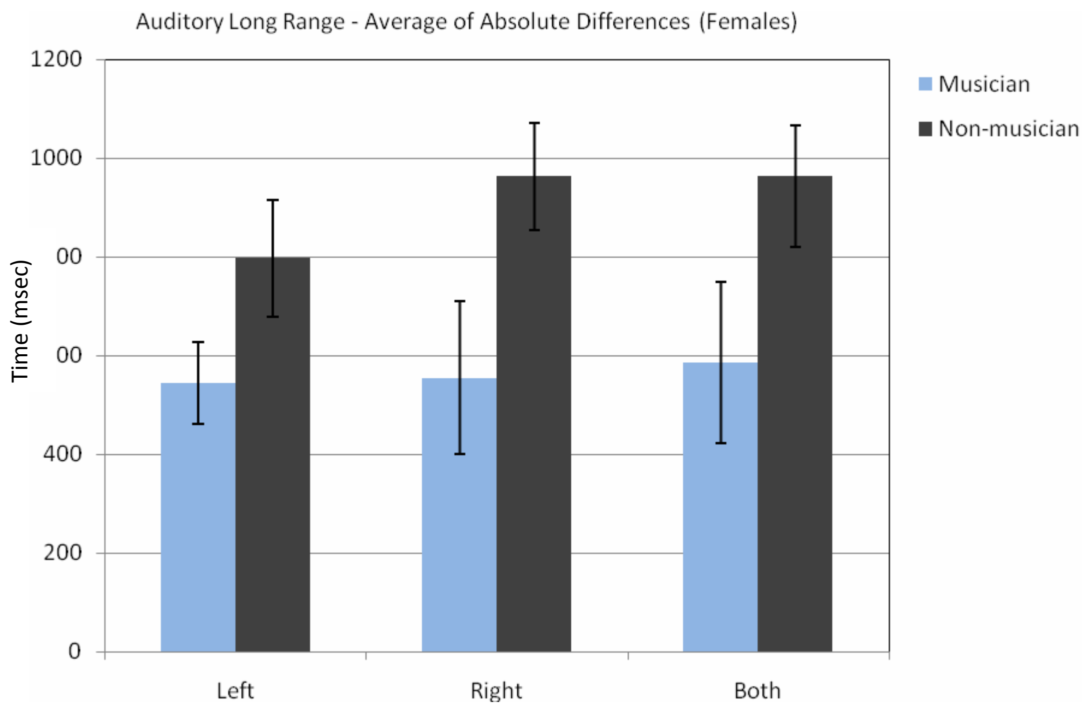

Fig. 3 The average of ascending and descending sequences' absolute difference between the female subjects' decision and the standard stimulus (3000 msec.).

Table 3. The Average of the Absolute Differences for Ascending and Descending Auditory Long Range Sequences for Female Subjects

	Left.	SD	Right	SD	Both	SD
Musician	544.64	221.60	554.69	438.69	585.94	462.83
Non-mus.	796.88	412.97	963.54	376.38	963.54	355.02

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending / Descending) for the female group indicated that there was a significant difference between musicians and non-musicians [$F(1, 110) = 18.39$, $p < 0.001$]. Absolute differences for musicians were smaller than non-musicians. There was also significant difference for ascending / descending order [$F(1, 110) = 3.98$, $p < 0.05$]. The absolute difference for descending order was bigger. This test did not show any significant interaction between the groups, ears and ascending or descending order (for group x side [$F(2, 110) = 0.39$, $p = 0.53$], for group x ascending/descending [$F(1, 110) = 0.05$, $p = 0.81$], for side x ascending/descending [$F(2, 110) = 1.02$, $p = 0.31$], for group x side x ascending/descending [$F(2, 110) = 1.37$, $p = 0.24$]).

Auditory Modality - Males

Fig. 4 shows the time estimations (absolute times) for the auditory long range sequence for musicians and non-musicians in the male group. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 4 summarizes the absolute time data for the long range auditory ascending and descending conditions (all numbers are in milliseconds, standard stimulus is 3000 msec).

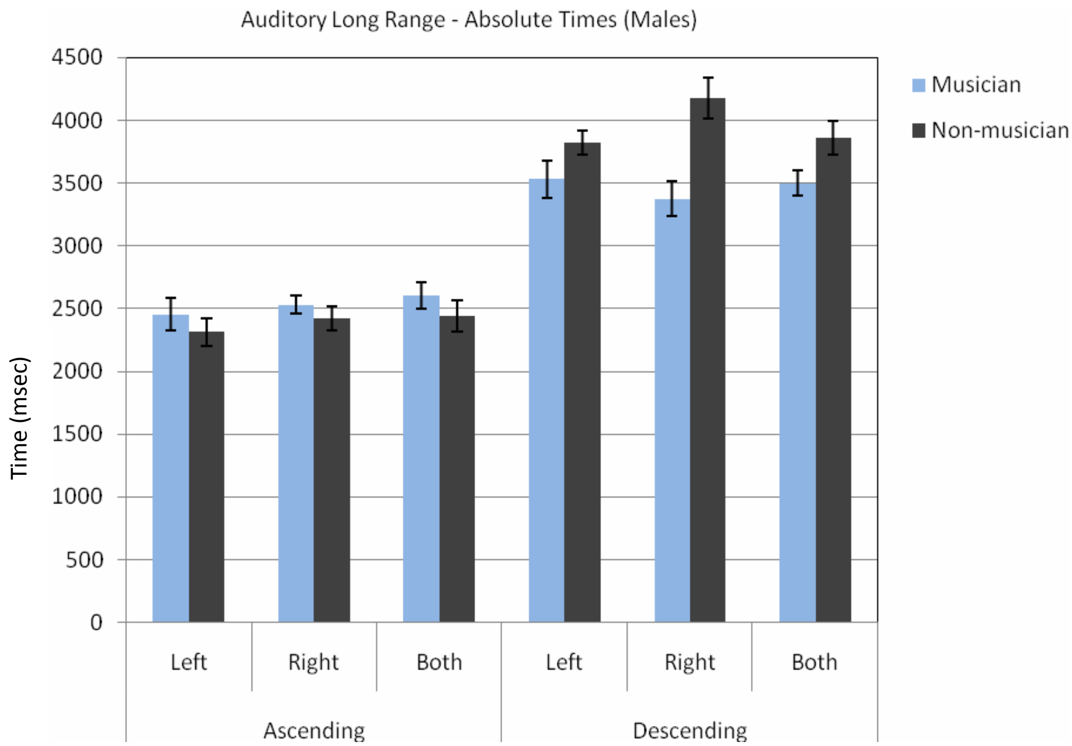

Fig. 4 The absolute average times (in milliseconds) at which male subjects decided that the tones were of equal length for ascending and descending tone sequences.

Table 4. Absolute Times for Long Range Auditory Signals in Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	2453.13	365.58	2531.25	206.63	2607.14	283.47
Non-mus.	2312.50	354.78	2425.00	307.32	2437.50	391.98
Descending						
Musician	3531.25	426.52	3375.00	400.89	3500.00	237.17
Non-mus.	3825.00	301.62	4175.00	507.58	3862.50	430.80

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for males in the auditory long range time estimation task showed a significant difference between groups [$F(1, 100) = 4.46$, $p < 0.05$]. Musicians were closer to the standard stimulus than non-musicians. There was no significant difference between sides [$F(2, 100) = 1.19$, $p = 0.27$]. There was a significant difference between ascending and descending orders [$F(1, 100) = 324.57$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(2, 100) = 0.04$, $p = 0.84$], for group x ascending/descending [$F(1, 100) = 0.05$, $p = 0.88$], for side x ascending/descending [$F(2, 100) = 0.09$, $p = 0.76$], for group x side x ascending/descending [$F(2, 100) = 0.05$, $p = 0.84$]).

Fig. 5 shows the absolute difference between the subjects' absolute response time and the standard stimulus for the auditory long range ascending and descending sequences. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 5 summarizes the absolute difference data for the long range auditory ascending and descending conditions (all numbers are in milliseconds).

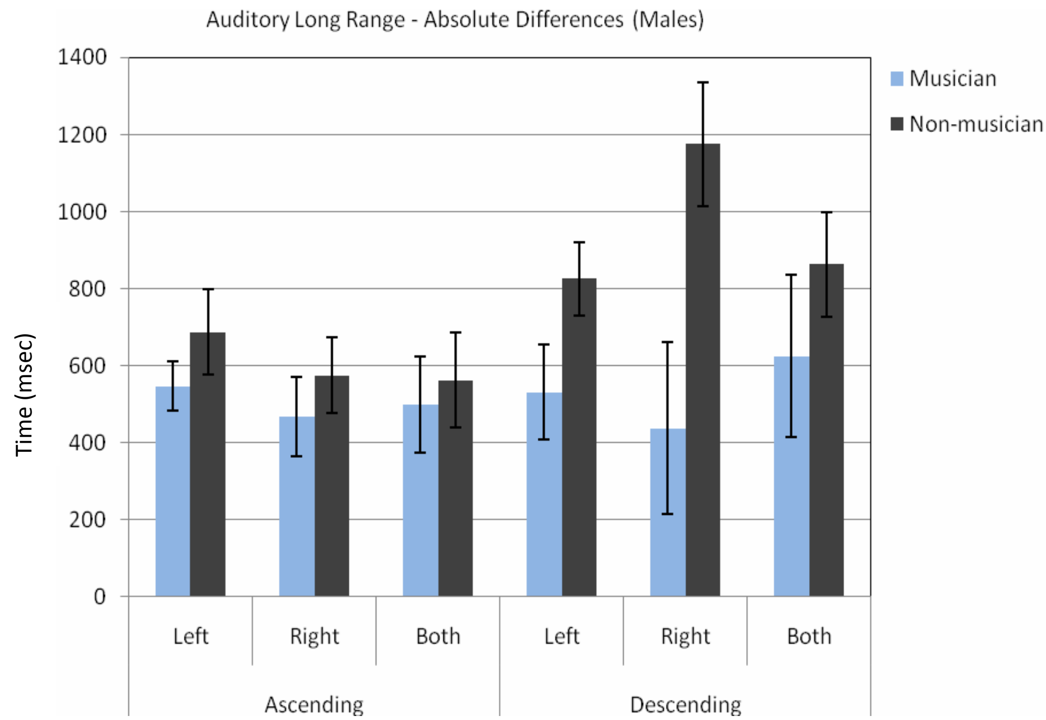

Fig. 5 The absolute difference between the male subjects' decision and the standard stimulus (3000 msec.) for ascending and descending tone sequences.

Table 5. Absolute Differences for Long range Auditory Signals in Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	546.88	365.58	468.75	208.63	421.88	274.98
Non-mus.	687.50	354.78	575.00	307.32	562.50	391.98
Descending						
Musician	531.25	426.52	437.50	320.43	625.00	365.96
Non-mus.	825.00	301.62	1175.00	507.58	862.50	430.80

Fig. 6 shows the average of absolute differences for ascending and descending auditory long range sequences. The averages are given separately for left ear, right ear and both ears. Table 6 summarizes the average of absolute differences for ascending and descending auditory long range sequences.

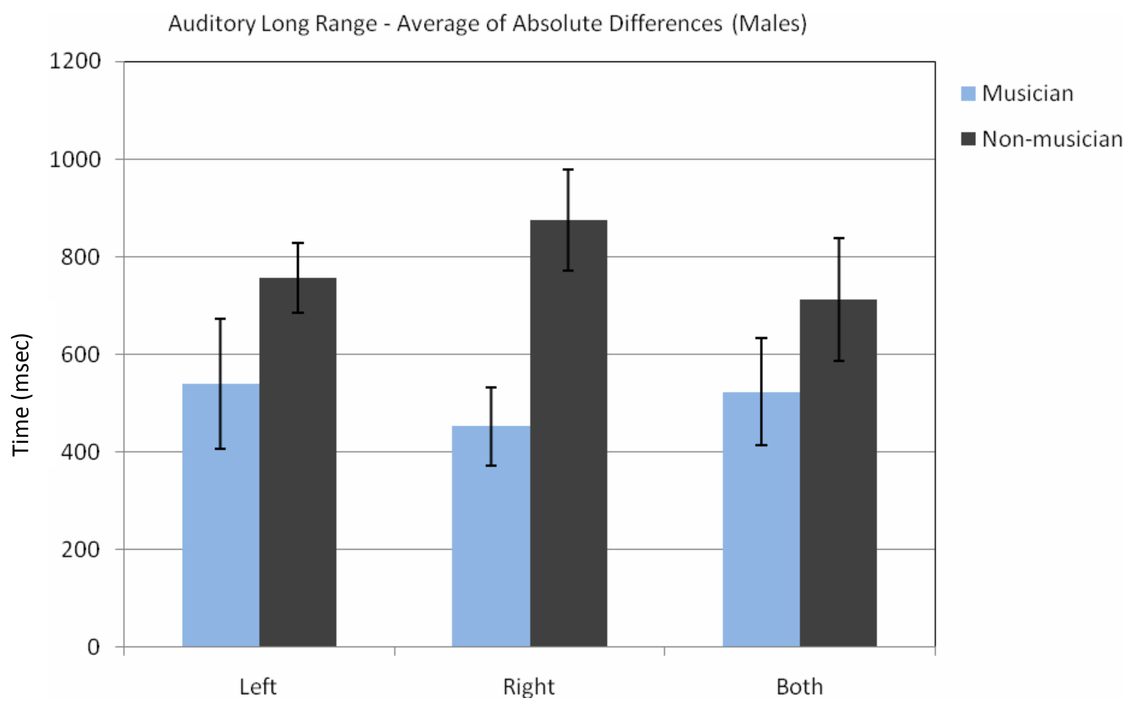

Fig. 6 The average of ascending and descending sequences' absolute difference between the male subjects' decision and the standard stimulus (3000 msec.).

Table 6. The Average of the Absolute Differences for Ascending and Descending Auditory Long Range Sequences for Male Subjects

	Left.	SD	Right	SD	Both	SD
Musician	539.06	376.39	453.13	225.97	523.44	307.89
Non-mus.	756.25	227.17	875.00	325.43	712.50	398.78

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending / Descending) for the male group indicated that there was a significant difference between musicians and non-musicians [$F(1, 100) = 14.80$, $p < 0.001$]. The absolute differences for musicians were smaller than non-musicians. There was also significant difference for ascending / descending order [$F(1, 100) = 9.11$, $p < 0.01$]. The absolute difference for the descending order was bigger than the ascending order. There was no difference for sides [$F(2, 100) = 0.12$, $p = 0.72$]. This test did not show any significant interaction between the groups, ears and ascending or descending order (for group x side [F(1, 100) = 0.02, p = 0.87], for group x ascending/descending [F(1, 100) = 4.19, p = 0.43], for side x ascending/descending [F(2, 100) = 1.15, p = 0.28], for group x side x ascending/descending [F(2, 100) = 0.02, p = 0.87]).

Tactile Modality - Females

Fig. 7 shows the time estimations (absolute times) for the tactile long range sequence for musicians and non-musicians in female group. The ascending and descending sequences are given separately for left hand and right hand. Table 7 summarizes the absolute time data for the long range tactile ascending and descending conditions (all numbers are in milliseconds, standard stimulus is 3000 msec).

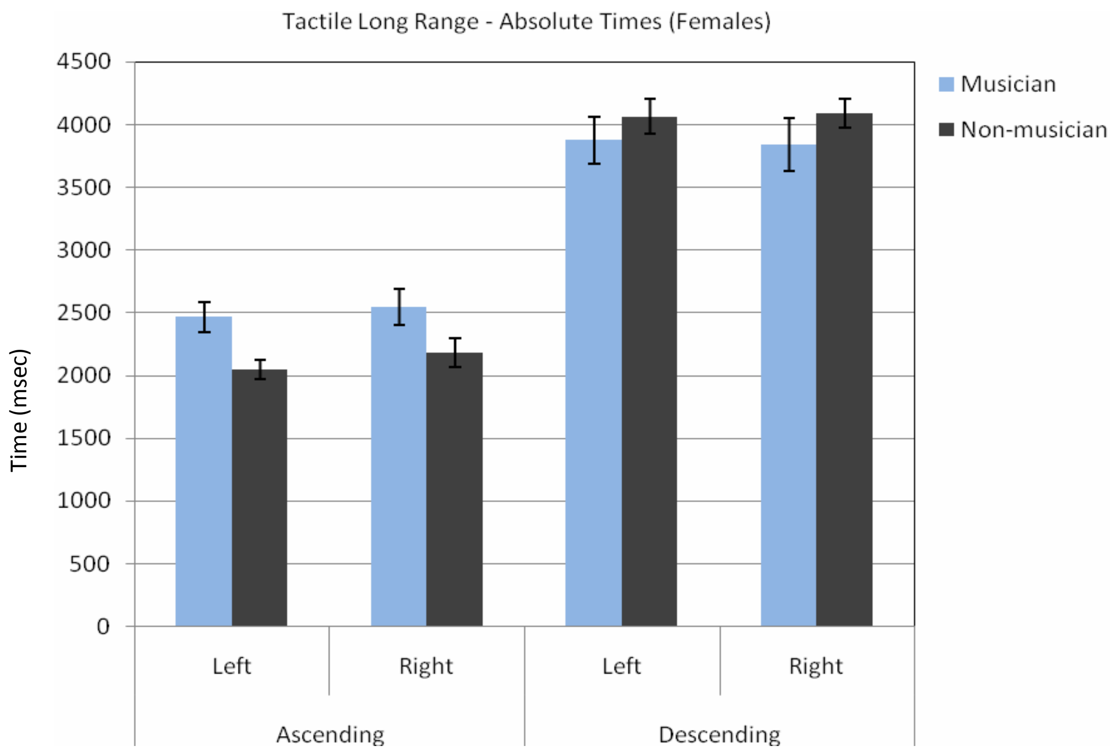

Fig. 7 The absolute average times (in milliseconds) at which female subjects decided that the vibrations were of equal length for ascending and descending vibratory sequences.

Table 7. Absolute Times for Long Range Tactile Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD
Ascending				
Musician	2468.75	339.05	2546.88	411.54
Non-mus.	2045.45	257.83	2181.82	380.64
Descending				
Musician	3875.00	467.71	3839.29	562.33
Non-mus.	4062.50	438.00	4088.64	381.01

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for females in the tactile long range time estimation task showed no significant difference between groups [F(1, 67) = 0.10, p = 0.74]. There was no significant difference between sides [F(1, 67) = 0.41, p

= 0.52]. There was significant difference between ascending and descending orders [$F(1, 67) = 331.05$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(1, 67) = 0.01$, $p = 0.89$], for group x ascending/descending [$F(1, 67) = 0.16$, $p = 0.72$], for side x ascending/descending [$F(1, 67) = 0.14$, $p = 0.70$], for group x side x ascending/descending [$F(1, 67) = 0.13$, $p = 0.71$]).

Fig. 8 shows the absolute difference between the subjects' absolute response and the standard stimulus for the tactile long range ascending and descending sequences. The ascending and descending sequences are given separately for the left hand and the right hand. Table 8 summarizes the absolute difference data for the long range tactile ascending condition (all numbers are in milliseconds).

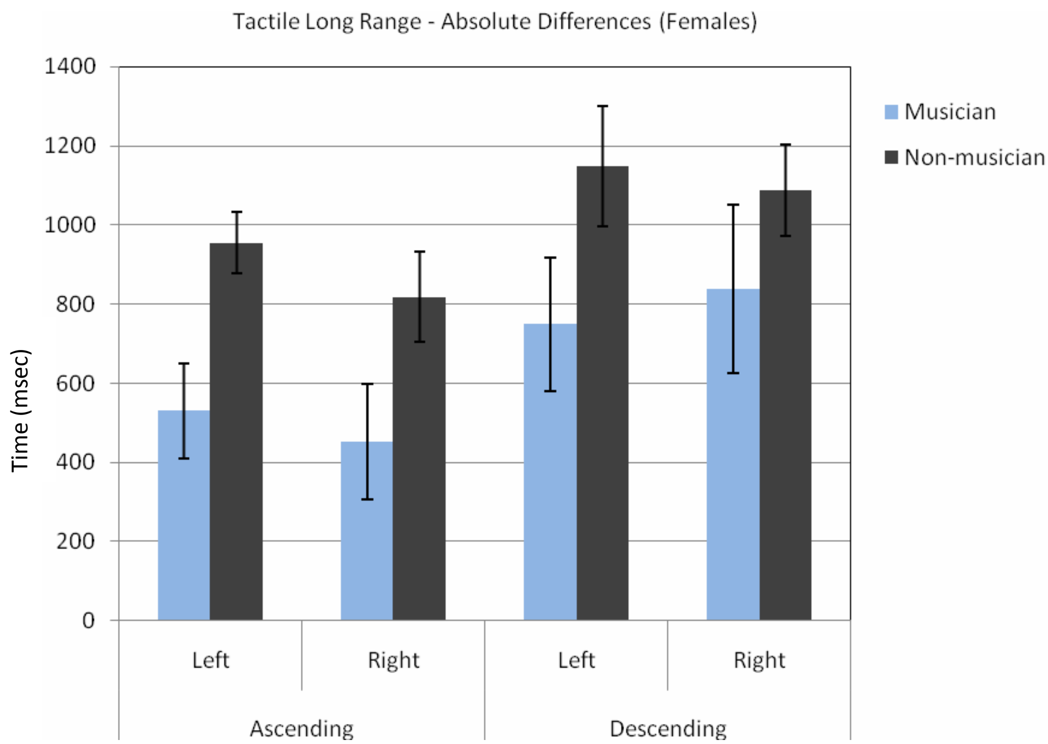

Fig. 8 The absolute difference between the female subjects' decision and the standard stimulus (3000 msec.) for ascending and descending vibratory sequences.

Table 8. Absolute Differences for Long Range Tactile Ascending Order for Female Subjects

	Left	SD	Right	SD
Ascending				
Musician	531.25	339.05	453.13	411.54
Non-mus.	954.55	257.83	818.18	380.64
Descending				
Musician	750.00	477.16	839.29	562.33
Non-mus.	1147.73	502.55	1088.64	381.01

Fig. 9 shows the average of absolute differences for ascending and descending tactile long range sequences. The averages are given separately for the left hand and the right hand. Table 9 summarizes the average of absolute differences for ascending and descending auditory long range sequences.

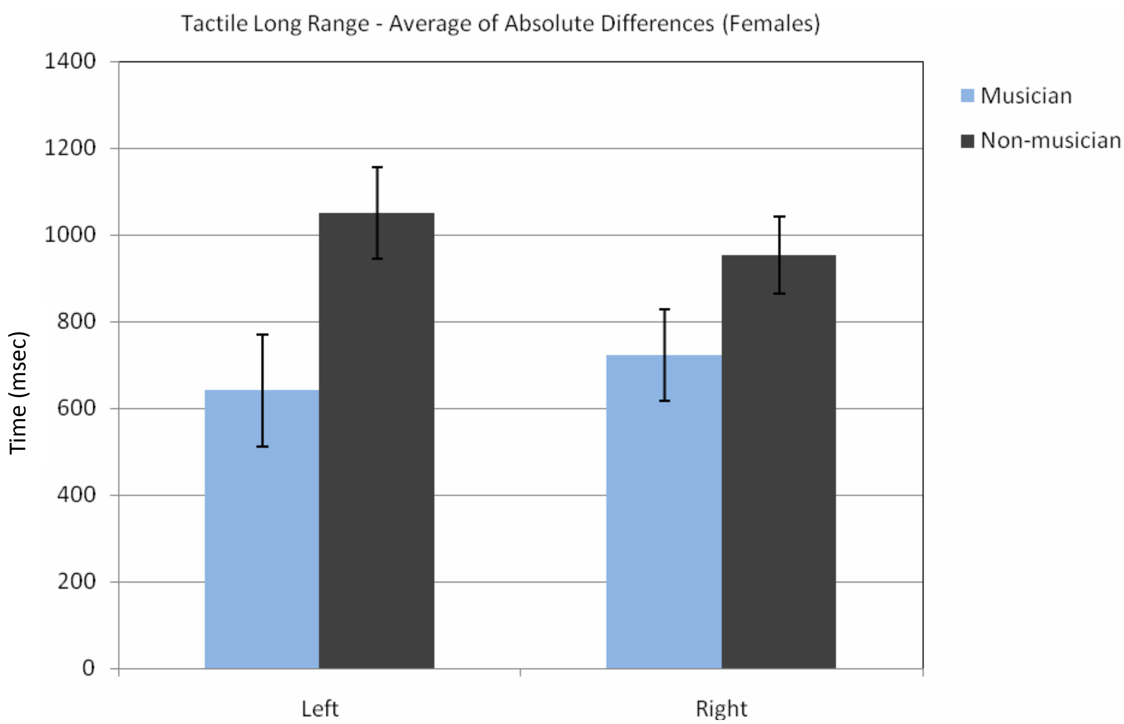

Fig. 9 The average of ascending and descending sequences' absolute difference between the female subjects' decision and the standard stimulus (3000 msec.). Lower numbers mean better interval time discrimination.

Table 9. The Average of the Absolute Differences for Ascending and Descending Tactile Long Range Sequences for Female Subjects

	Left.	SD	Right	SD
Musician	640.63	367.10	669.64	429.56
Non-mus.	1051.14	351.13	953.41	297.60

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending/Descending) indicated a significant difference between musicians and non-musicians [$F(1, 67) = 14.04$, $p < 0.001$]. The absolute errors for musicians were smaller than the absolute error for non-musicians. There was no significant difference between hands [$F(1, 67) = 0.39$, $p = 0.53$]. There was a significant difference for ascending / descending order [$F(1, 67) = 7.27$, $p < 0.01$]. The absolute error for descending was bigger than the one for ascending. There were no interactions between the groups, hands and order of the sequences (for group x side [$F(1, 67) = 0.25$, $p = 0.61$], for group x ascending/descending [$F(1, 67) = 0.12$, $p = 0.72$], for side x ascending/descending [$F(1, 67) = 0.35$, $p = 0.55$], for group x side x ascending/descending [$F(1, 67) = 0.05$, $p = 0.81$]).

Tactile Modality - Males

Fig. 10 shows the time estimations (absolute times) for the tactile long range sequence for musicians and non-musicians in male group. The ascending and descending sequences are given separately for left hand and right hand. Table 10 summarizes the absolute time data for the long range tactile ascending and descending conditions (all numbers are in milliseconds, standard stimulus is 3000 msec).

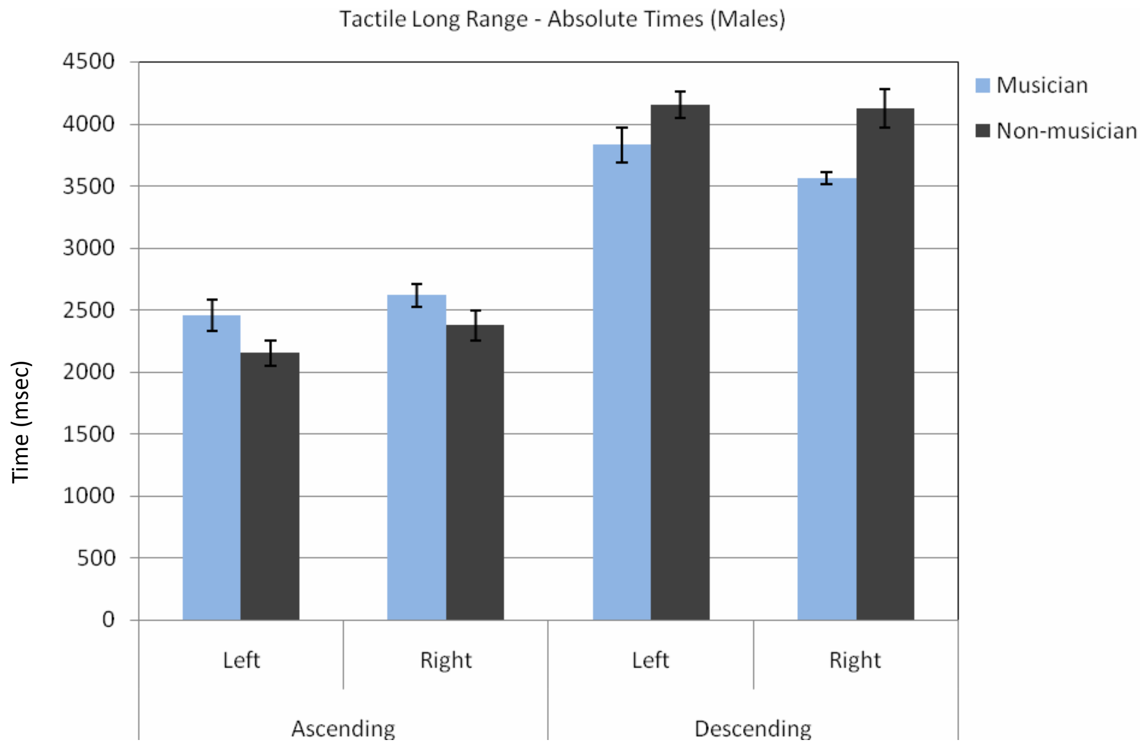

Fig. 10 The absolute average times (in milliseconds) at which male subjects decided that the vibrations were of equal length for ascending and descending vibratory sequences.

Table 10. Absolute Times for Long Range Tactile Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD
Ascending				
Musician	2458.33	369.75	2618.00	276.71
Non-mus.	2150.00	332.29	2375.00	381.88
Descending				
Musician	3828.13	389.24	3562.50	149.40
Non-mus.	4150.00	337.47	4125.00	493.01

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for males in the tactile long range time estimation task showed no significant difference between groups [$F(1, 67) = 0.74$, $p = 0.39$]. There was no significant difference between sides [$F(1, 67) = 0.03$, p

= 0.95]. There was significant difference between ascending and descending orders [$F(1, 67) = 341.82$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(1, 67) = 1.11$, $p = 0.29$], for group x ascending/descending [$F(1, 67) = 1.37$, $p = 0.25$], for side x ascending/descending [$F(1, 67) = 1.14$, $p = 0.63$], for group x side x ascending/descending [$F(1, 67) = 0.60$, $p = 0.44$]).

Fig. 11 shows the absolute difference between the subjects' absolute response and the standard stimulus for the tactile long range ascending and descending sequences. The ascending and descending sequences are given separately for the left hand and the right hand. Table 11 summarizes the absolute difference data for the long range tactile ascending condition (all numbers are in milliseconds).

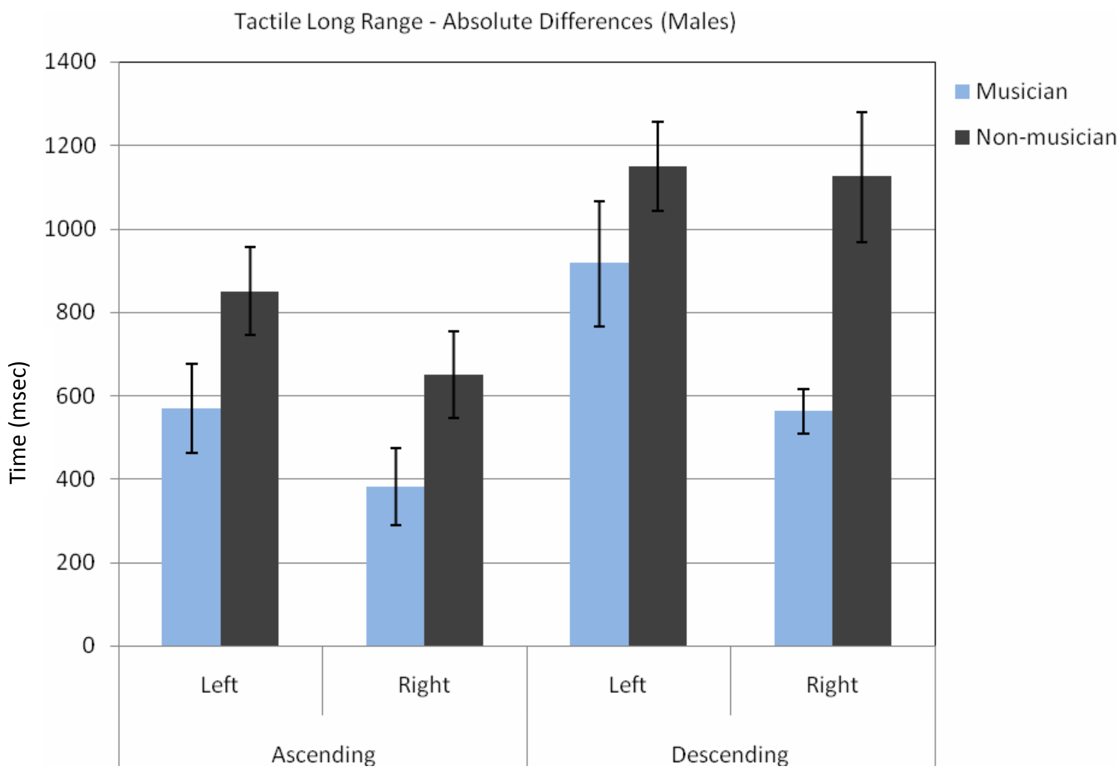

Fig. 11 The absolute difference between the male subjects' decision and the standard stimulus (3000 msec.) for ascending and descending vibratory sequences.

Table 11. Absolute Differences for Long Range Tactile Ascending Order for Male Subjects

	Left	SD	Right	SD
Ascending				
Musician	569.44	319.37	382.00	276.71
Non-mus.	850.00	332.29	650.00	332.29
Descending				
Musician	916.67	450.69	562.50	149.40
Non-mus.	1150.00	337.47	1125.00	493.01

Fig. 12 shows the average of absolute differences for ascending and descending tactile long range sequences. The averages are given separately for the left hand and the right hand. Table 12 summarizes the average of absolute differences for ascending and descending auditory long range sequences.

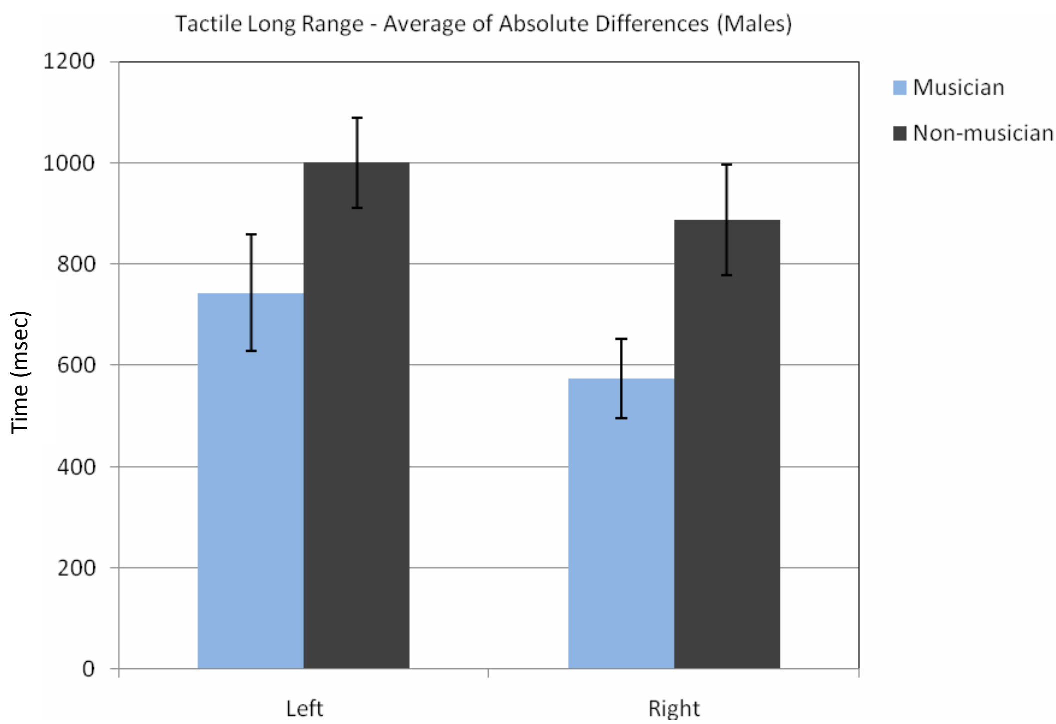

Fig. 12 The average of ascending and descending sequences' absolute difference between the male subjects' decision and the standard stimulus (3000 msec.). Lower numbers mean better interval time discrimination.

Table 12. The Average of the Absolute Differences for Ascending and Descending Tactile Long Range Sequences for Male Subjects

	Left.	SD	Right	SD
Musician	743.06	344.38	574.25	222.78
Non-mus.	1000.00	282.60	887.50	347.11

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending/Descending) indicated a significant difference between musicians and non-musicians [$F(1, 67) = 16.67$, $p < 0.001$]. The absolute errors for musicians were smaller than the one for non-musicians. There was also a significant difference between hands [$F(1, 67) = 5.32$, $p = 0.05$]. The right hand had smaller absolute difference than the left hand. There was a significant difference for ascending / descending order [$F(1, 67) = 16.47$, $p < 0.001$]. The absolute difference for descending order was bigger than the one for ascending order. There were no significant interactions between the groups, hands and order of the sequences (for group x side [$F(1, 67) = 0.87$, $p = 0.35$], for group x ascending/descending [$F(1, 67) = 0.54$, $p = 0.46$], for side x ascending/descending [$F(1, 67) = 0.01$, $p = 0.92$], for group x side x ascending/descending [$F(1, 67) = 1.08$, $p = 0.30$]).

Short Range Time Estimation

Auditory Modality - Females

Fig. 13 shows the time estimations (absolute times) for the auditory short range sequence for musicians and non-musicians in the female group. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 13 summarizes the absolute time data for the short range auditory ascending and descending conditions (all numbers are in milliseconds, standard stimulus is 500 msec).

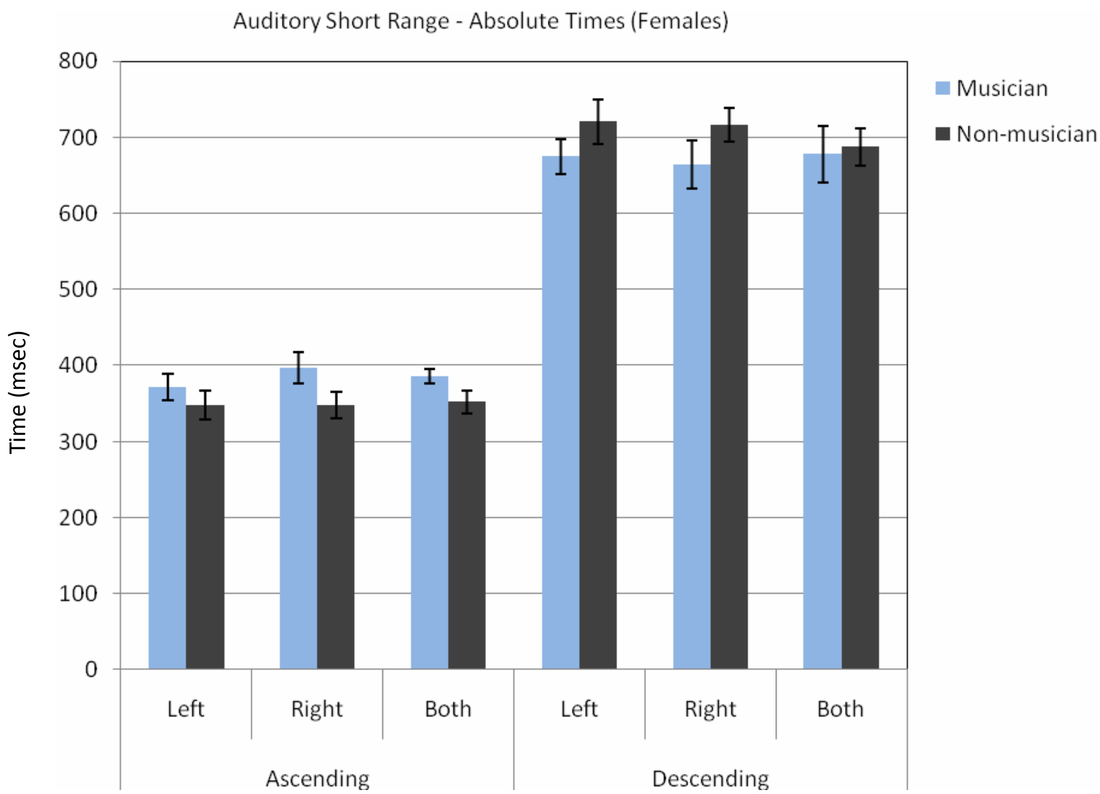

Fig. 13 The absolute average times (in milliseconds) at which female subjects decided that the tones were of equal length for ascending and descending tone sequences.

Table 13. Absolute Times for Short Range Auditory Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	371.88	50.78	396.88	58.92	385.71	24.40
Non-mus.	347.92	66.11	347.92	58.83	352.08	63.79
Descending						
Musician	675.00	61.24	664.29	85.22	678.13	103.89
Non-mus.	720.83	102.71	716.67	74.87	687.50	82.92

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for females in the short range time estimation task showed no significant difference between groups [$F(1, 112) = 0.04$, $p = 0.83$]. There was no significant difference between sides [$F(2, 112) = 0.05$, $p =$

0.81]. There was a significant difference between ascending and descending orders [$F(1, 112) = 630.27$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(2, 112) = 0.68$, $p = 0.40$], for group x ascending/descending [$F(1, 112) = 0.51$, $p = 0.33$], for side x ascending/descending [$F(2, 112) = 0.61$, $p = 0.43$], for group x side x ascending/descending [$F(2, 112) = 0.22$, $p = 0.63$]).

Fig. 14 shows the absolute difference between the subjects' absolute response and the standard stimulus for the auditory short range ascending and descending sequences. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 14 summarizes the absolute difference data for the short range auditory ascending and descending conditions (all numbers are in milliseconds).

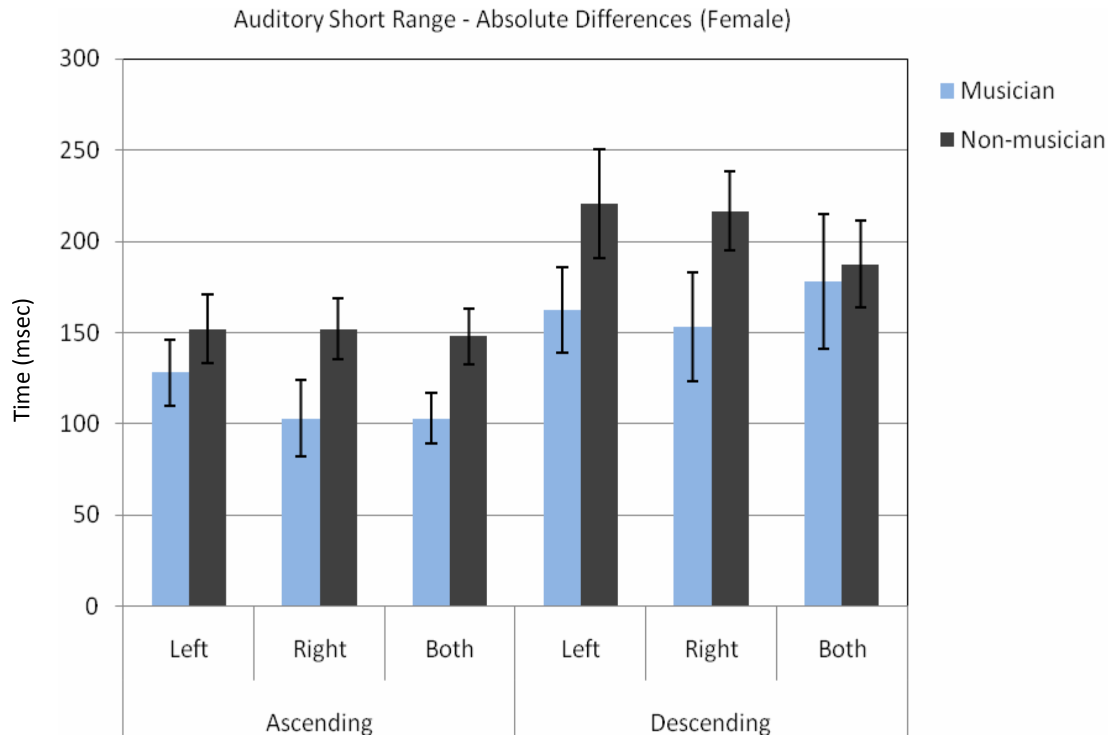

Fig. 14 The absolute differences between the female subjects' decision and the standard stimulus (500 msec.) for ascending and descending tone sequences.

Table 14. Absolute Differences for Short Range Auditory Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	128.13	50.78	103.13	58.92	103.13	38.82
Non-mus.	152,08	66.11	152.08	58.83	147.92	53.79
Descending						
Musician	162.50	66.82	153.13	84.98	178.13	103.89
Non-mus.	220.83	102.71	216.67	74.87	187.50	82.92

Fig. 15 shows the average of absolute differences for ascending and descending auditory short range sequences. The averages are given separately for left ear, right ear and both ears. Table 15 summarizes the average of absolute differences for ascending and descending auditory short range sequences.

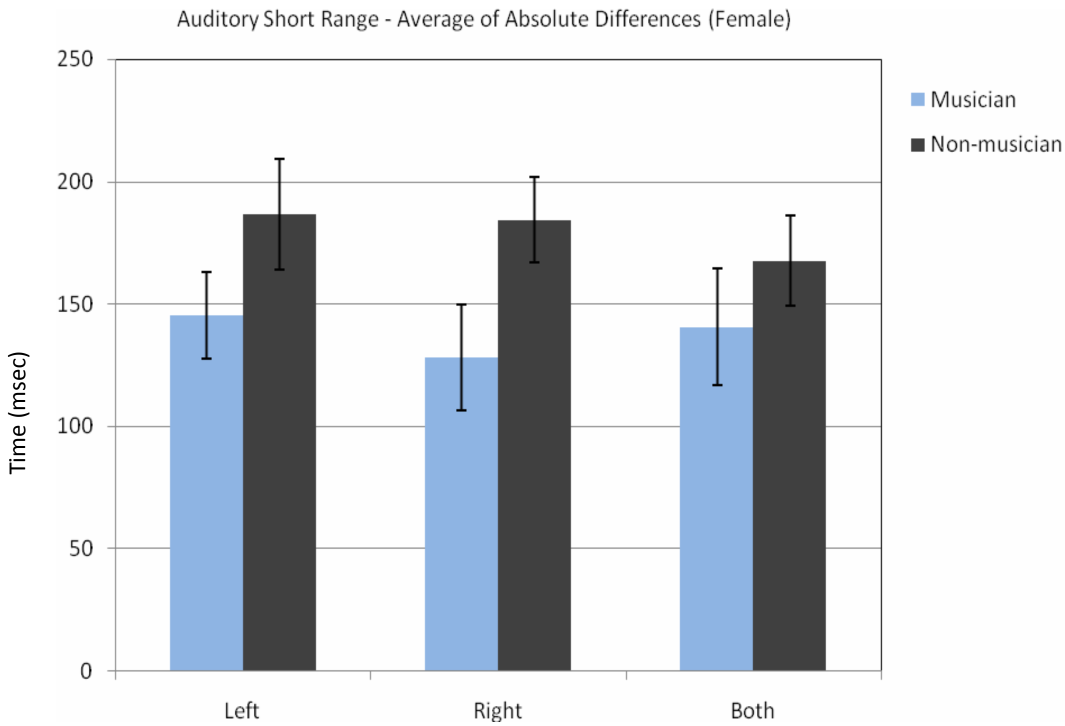

Fig. 15 The average of ascending and descending sequences' absolute difference between the female subjects' decision and the standard stimulus (500 msec.).

Table 15. The Average of the Absolute Differences for Ascending and Descending Auditory Short Range Sequences for Female Subjects

	Left.	SD	Right	SD	Both	SD
Musician	145,31	49.97	128,13	60.78	140,63	67.40
Non-mus.	186,46	78.42	184,38	60.57	167,71	63.17

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending/Descending) also showed that there was a significant difference between musicians and non-musicians [$F(1, 112) = 8.80$, $p < 0.01$]. The absolute differences for musicians were smaller than the one for non-musicians. There was also significant difference between ascending and descending order [$F(1, 112) = 17.28$, $p < 0.001$]. The absolute difference for descending was bigger than the one for ascending. There was no interaction between the groups, ears, and ascending / descending order (for group x side [F(2, 112) = 0.08, p = 0.77], for group x ascending/descending [F(1, 112) = 0.08, p = 0.78], for side x ascending/descending [F(2, 112) = 0.01, p = 0.93], for group x side x ascending/descending [F(2, 112) = 1.45, p = 0.23]).

Auditory Modality - Males

Fig. 16 shows the time estimations (absolute times) for the auditory short range sequence for musicians and non-musicians in the male group. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 16 summarizes the absolute time data for the short range auditory ascending and descending conditions (all numbers are in milliseconds, standard stimulus is 500 msec).

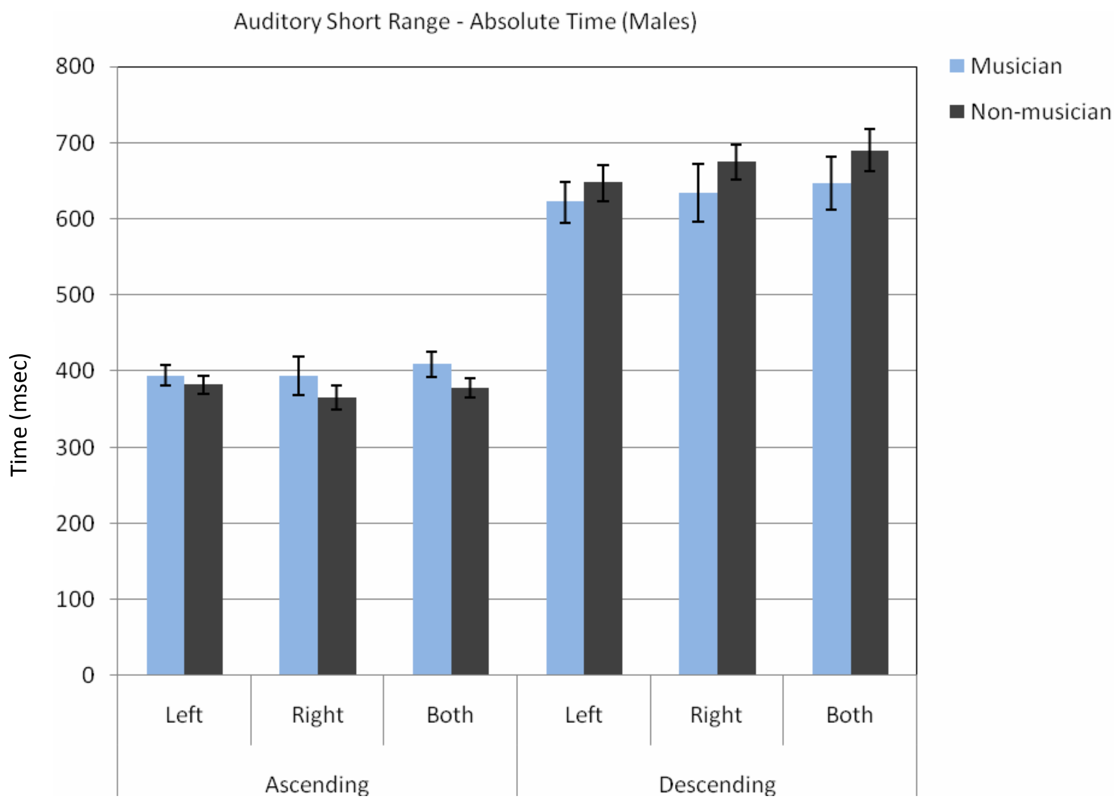

Fig. 16 The absolute average times (in milliseconds) at which male subjects decided that the tones were of equal length for ascending and descending tone sequences.

Table 16. Absolute Times for Short Range Auditory Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	394.44	41.04	393.75	70.39	409.38	46.17
Non-mus.	382.50	37.36	365,00	50.28	377.50	39.88
Descending						
Musician	622.22	81.44	634.38	106.85	646.88	99.50
Non-mus.	647.50	75.87	675.00	71.69	690.00	87.56

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for males in the auditory short range time estimation task showed no significant difference between groups [$F(1, 102) = 0.23$, $p = 0.62$]. There was no significant difference between sides [$F(2, 102) = 0.05$,

$p = 1.42$]. There was a significant difference between ascending and descending orders [$F(1, 102) = 416.67$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(2, 102) = 0.01$, $p = 0.97$], for group x ascending/descending [$F(1, 102) = 0.31$, $p = 0.23$], for side x ascending/descending [$F(2, 112) = 0.89$, $p = 0.34$], for group x side x ascending/descending [$F(2, 112) = 0.33$, $p = 0.56$]).

Fig. 17 shows the absolute difference between the subjects' absolute response and the standard stimulus for the auditory short range ascending and descending sequences. The ascending and descending sequences are given separately for left ear, right ear and both ears. Table 17 summarizes the absolute difference data for the short range auditory ascending and descending conditions (all numbers are in milliseconds).

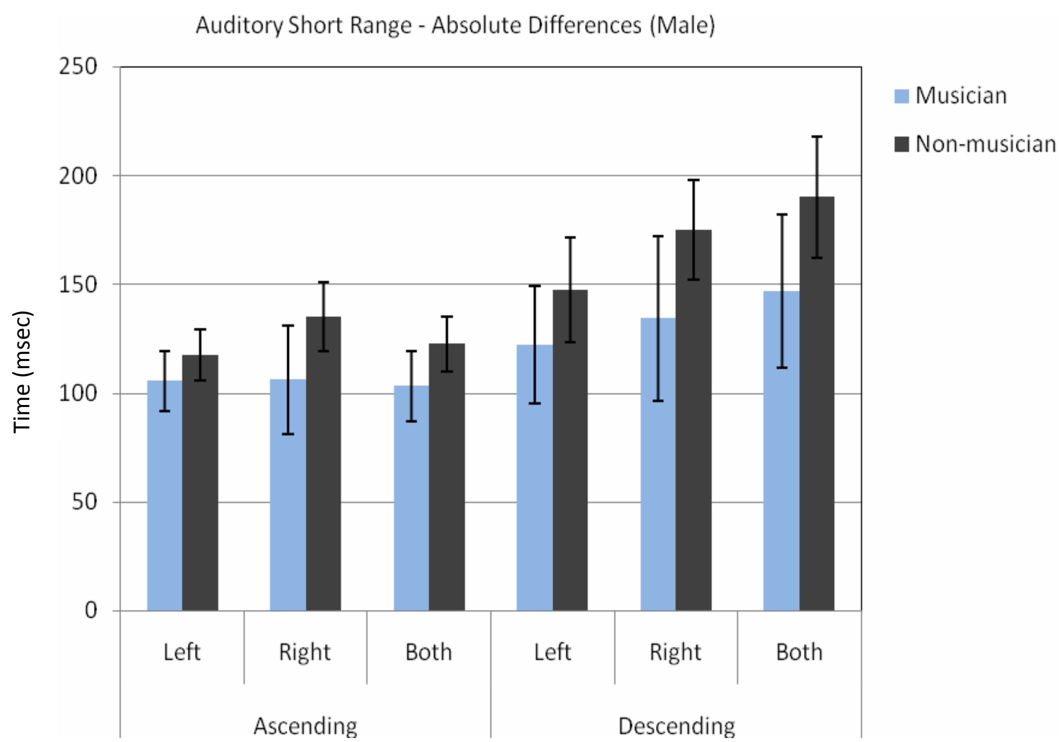

Fig. 17 The absolute difference between the male subjects' decision and the standard stimulus (500 msec.) for ascending and descending tone sequences.

Table 17. Absolute Differences for Short Range Auditory Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD	Both	SD
Ascending						
Musician	105.56	41.04	106.25	70.39	90.63	46.17
Non-mus.	117.50	37.36	135.00	50.28	122.50	39.88
Descending						
Musician	122.22	81.44	134.38	106.85	146.88	99.50
Non-mus.	147.50	75.87	175.00	71.69	190.00	87.56

Fig. 18 shows the average of absolute differences for ascending and descending auditory short range sequences. The averages are given separately for left ear, right ear and both ears. Table 18 summarizes the average of absolute differences for ascending and descending auditory short range sequences.

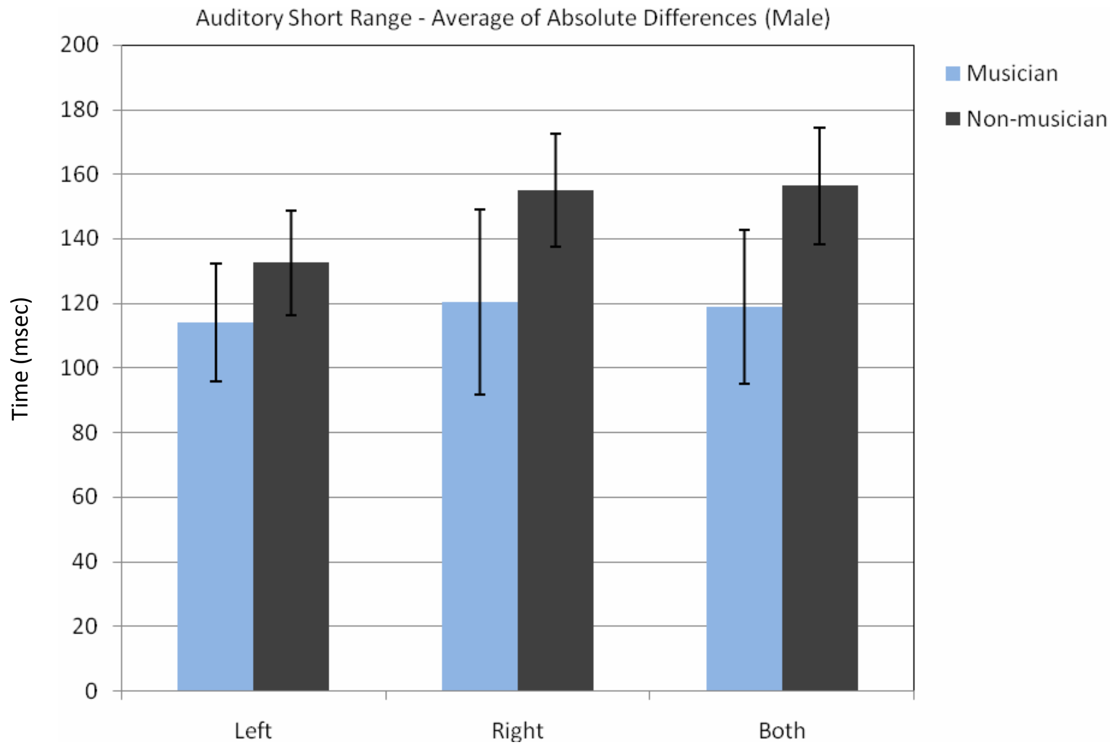

Fig. 18 The average of the absolute differences for ascending and descending auditory short range sequences for male subjects.

Table 18. The Average of the Absolute Differences for Ascending and Descending Auditory Short Range Sequences for Male Subjects

	Left	SD	Right	SD	Both	SD
Musician	113.89	54.65	120.31	81.27	118.75	67.48
Non-mus.	132.50	51.44	155.00	55.03	156.25	56.90

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending/Descending) showed that there was a significant difference between musicians and non-musicians [$F(1, 102) = 5.82$, $p < 0.05$]. The absolute differences for musicians were smaller than the one for non-musicians. There was significant difference between ascending descending order [$F(1, 102) = 9.86$, $p < 0.01$]. The absolute difference for descending order was bigger than the one for ascending order. There was no significant difference between sides [F(2, 102) =

1.13, $p < 0.30$]. There were no significant interactions between the groups, ears, and ascending / descending order (for group x side [$F(2, 102) = 0.20$, $p = 0.65$], for group x ascending/descending [$F(2, 102) = 0.13$, $p = 0.71$], for side x ascending/descending [$F(2, 102) = 1.14$, $p = 0.28$], for group x side x ascending/descending [$F(2, 102) = 0.01$, $p = 0.91$]).

Tactile Modality - Females

Fig. 19 shows the time estimations (absolute times) for the tactile short range sequence for musicians and non-musicians in the female group. The ascending and descending sequences are given separately for left hand and right hand. Table 19 summarizes the absolute time data for the short range tactile ascending and descending conditions (all numbers are in milliseconds).

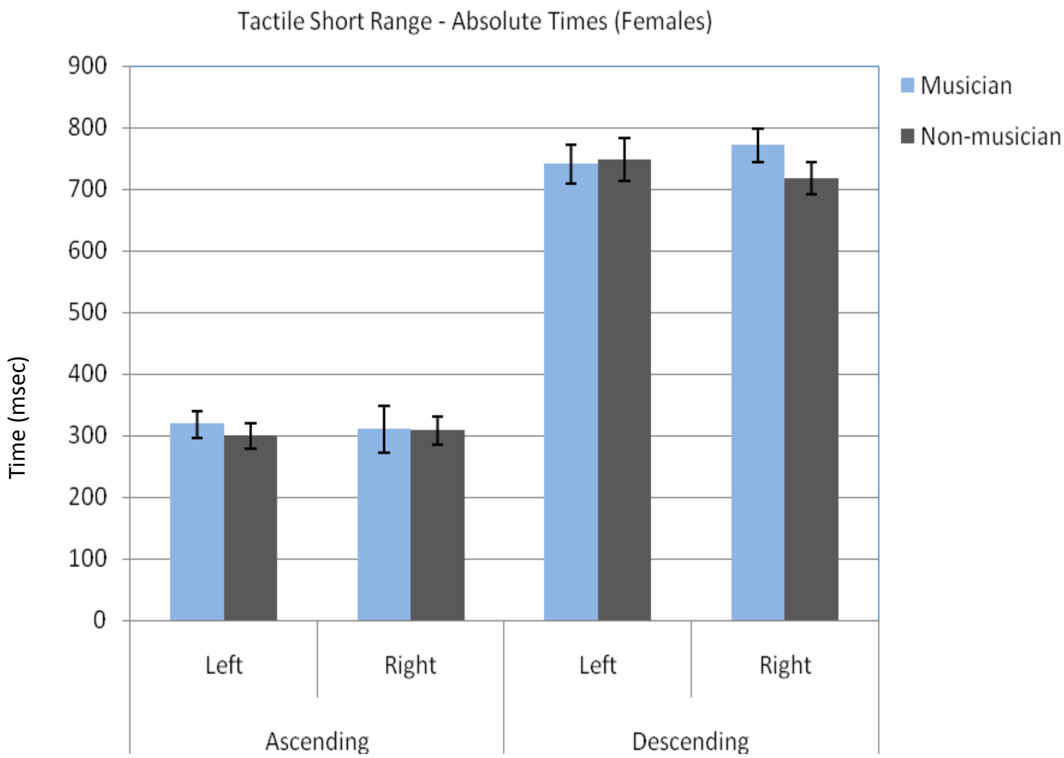

Fig. 19 The absolute average times (in milliseconds) at which female subjects decided that the vibrations were of equal length for ascending and descending vibratory sequences.

Table 19. Absolute Times for Short Range Tactile Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD
Ascending				
Musician	318.75	62.32	310.71	98.80
Non-mus.	300.00	68.01	309.09	76.05
Descending				
Musician	740.63	87.56	771.43	74.20
Non-mus.	747.73	115.90	718.18	83.73

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for females in the tactile short range time estimation task showed no significant difference between groups [$F(1, 66) = 0.64$, $p = 0.42$]. There was no significant difference between sides [$F(1, 66) = 0.01$, p

= 0.94]. There was significant difference between ascending and descending orders [$F(1, 66) = 476.18$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(1, 66) = 0.28$, $p = 0.59$], for group x ascending/descending [$F(1, 66) = 0.08$, $p = 0.87$], for side x ascending/descending [$F(1, 66) = 0.03$, $p = 0.89$], for group x side x ascending/descending [$F(1, 66) = 0.91$, $p = 0.34$]).

Fig. 20 shows the absolute difference between the subjects' absolute response and the standard stimulus for the tactile short range ascending and descending sequences. Ascending and descending sequences are given separately for the left hand and the right hand. Table 20 summarizes the absolute difference data for the short range tactile ascending and descending conditions (all numbers are in milliseconds).

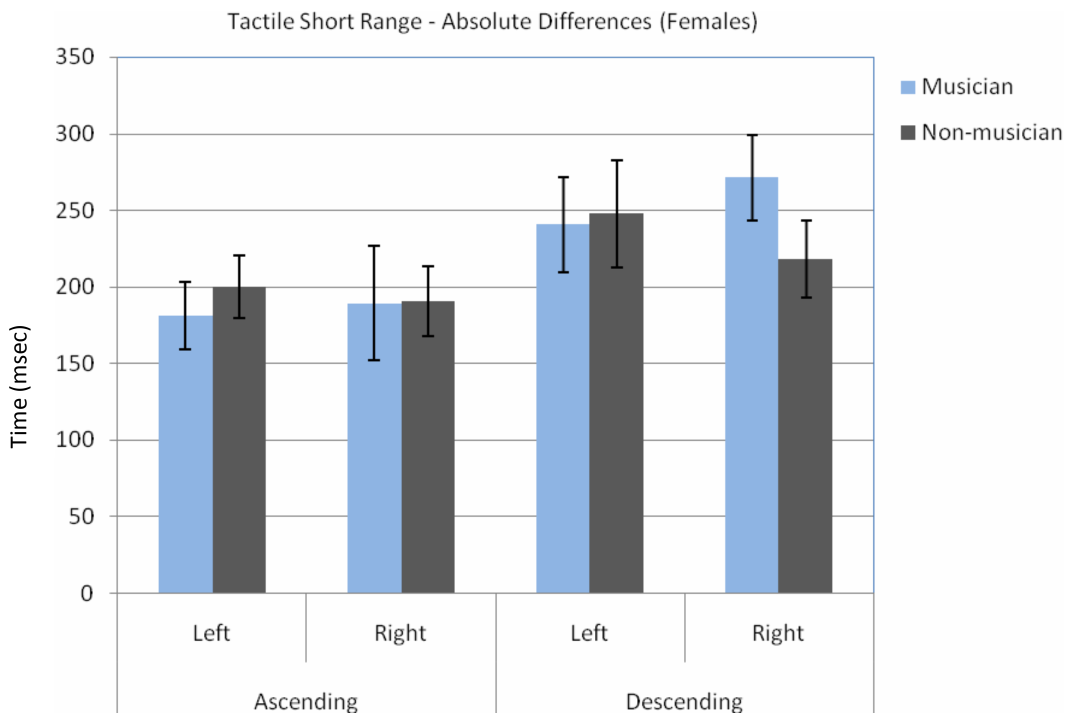

Fig. 20 The absolute difference between the female subjects' decision and the standard stimulus (500 msec.) for ascending and descending vibratory sequences.

Table 20. Absolute Differences for Short range Tactile Ascending and Descending Order for Female Subjects

	Left	SD	Right	SD
Ascending				
Musician	181.25	62.32	189.29	98.80
Non-mus.	200.00	68.01	190.91	76.05
Descending				
Musician	240.63	87.56	271.43	74.20
Non-mus.	247.73	115.90	218.18	83.73

Fig. 21 shows the average of absolute differences for ascending and descending tactile short range sequences. The averages are given separately for the left hand and the right hand. Table 21 summarizes the average of absolute differences for ascending and descending tactile short range sequences.

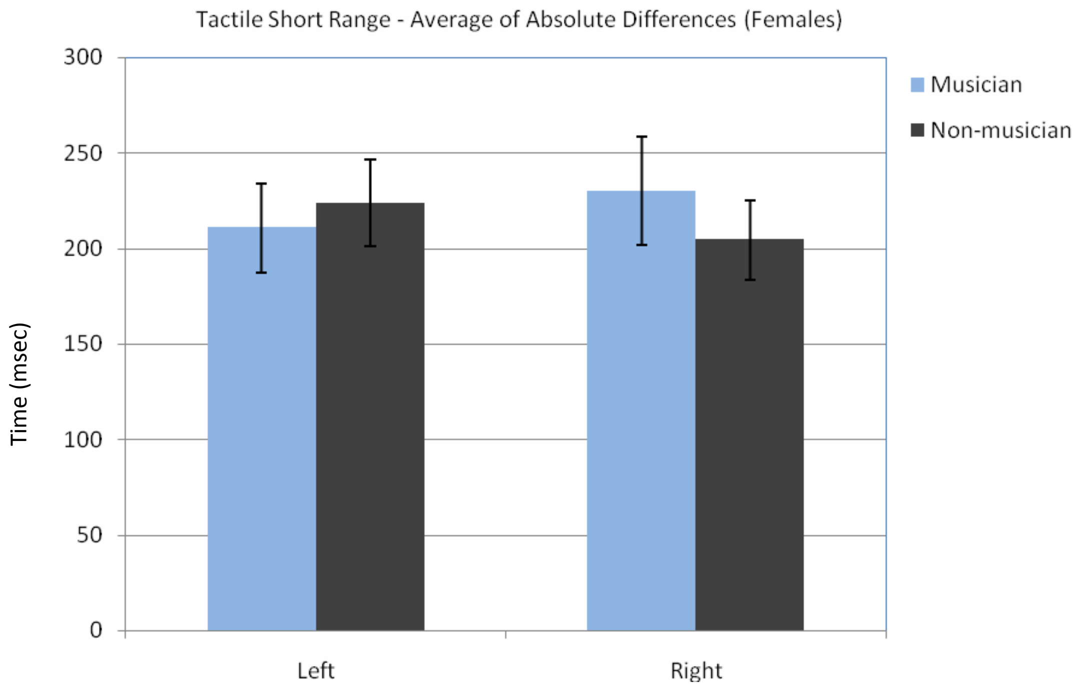

Fig. 21 The average of ascending and descending sequences' absolute difference between the female subjects' decision and the standard stimulus (500 msec.).

Table 21. The Average of the Absolute Differences for Ascending and Descending Tactile Short Range Sequences for Female Subjects

	Left.	SD	Right	SD
Musician	210.94	65.95	230.36	75.30
Non-mus.	223.86	75.72	204.55	68.53

A three way ANOVA for absolute differences with repeated measures on two factors (Group x Side x Ascending/Descending) showed that there was no significant difference between musicians and non-musicians ($F(1, 65) = 0.14$, $p = 0.71$) but it showed that there was a significant difference for ascending and descending sequences [$F(1, 65) = 7.02$, $p < 0.05$]. The absolute difference for descending order was bigger than the one for ascending order. There was no significant difference between sides [$F(1, 65) = 0.09$, $p = 0.76$]. No significant interaction was found between the groups, hands and ascending / descending order (for group x side [F(1,

65) = 1.16, p = 0.29], for group x ascending/descending [F(1, 65) = 0.42, p = 0.51], for side x ascending/descending [F(1, 65) = 0.01, p = 0.92], for group x side x ascending/descending [F(1, 65) = 0.15, p = 0.69]).

Tactile Modality - Males

Fig. 22 shows the time estimations (absolute times) for the tactile short range sequence for musicians and non-musicians in the male group. The ascending and descending sequences are given separately for left hand and right hand. Table 22 summarizes the absolute time data for the short range tactile ascending and descending conditions (all numbers are in milliseconds).

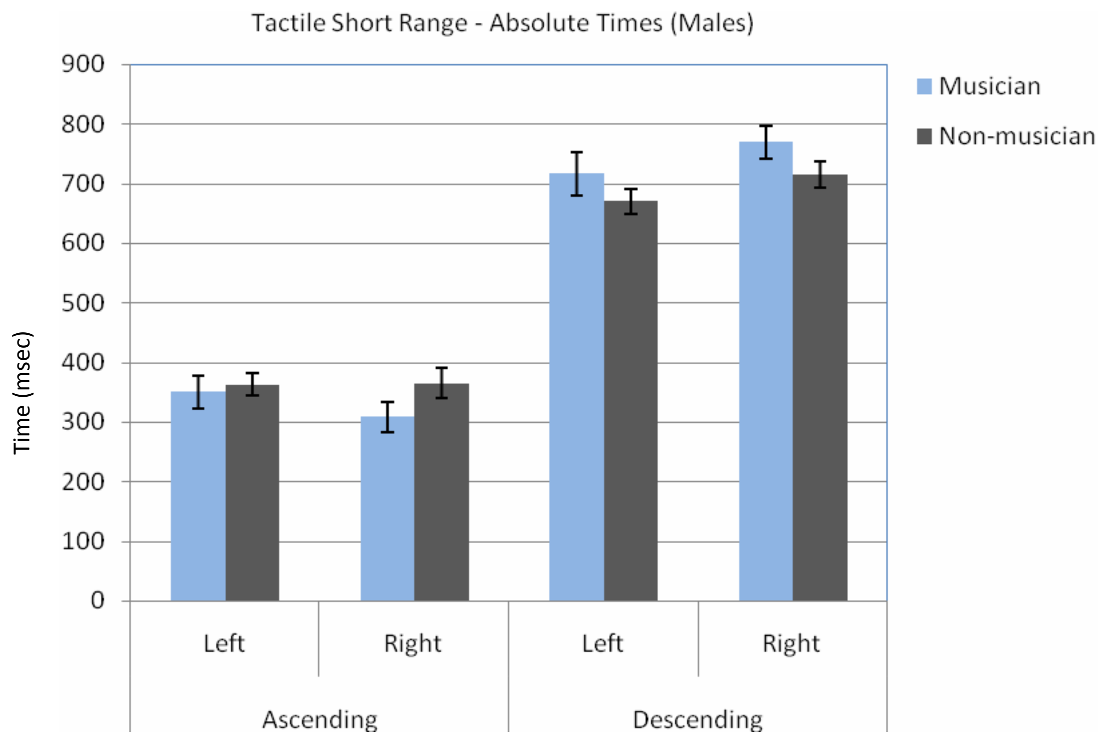

Fig. 22 The absolute average times (in milliseconds) at which male subjects decided that the vibrations were of equal length for ascending and descending vibratory sequences.

Table 22. Absolute Times for Short Range Tactile Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD
Ascending				
Musician	350,00	84.78	308,33	76.03
Non-mus.	362,50	60.38	365,00	80.10
Descending				
Musician	716,67	107.53	769,44	83.65
Non-mus.	670,00	67.49	715,00	69.92

A three way ANOVA for absolute times with repeated measures on two factors (Group x Side x Ascending/Descending) for males in the tactile short range time estimation task showed no significant difference between groups [F(1, 68) = 0.19, p = 0.66]. There was no significant difference between sides [F(1, 68) = 0.69, p = 0.41]. There was significant difference between ascending and descending orders

[$F(1, 68) = 411.41$, $p < 0.001$]. The absolute time for ascending order was closer to the standard stimulus. There were no significant interactions between groups, sides and ascending/descending order (for group x side [$F(1, 68) = 0.24$, $p = 0.61$], for group x ascending/descending [$F(1, 68) = 1.45$, $p = 0.22$], for side x ascending/descending [$F(1, 68) = 1.40$, $p = 0.27$], for group x side x ascending/descending [$F(1, 66) = 0.50$, $p = 0.48$]).

Fig. 23 shows the absolute difference between the subjects' absolute response and the standard stimulus for the tactile short range ascending and descending sequences. Ascending and descending sequences are given separately for the left hand and the right hand. Table 23 summarizes the absolute difference data for the short range tactile ascending and descending conditions (all numbers are in milliseconds).

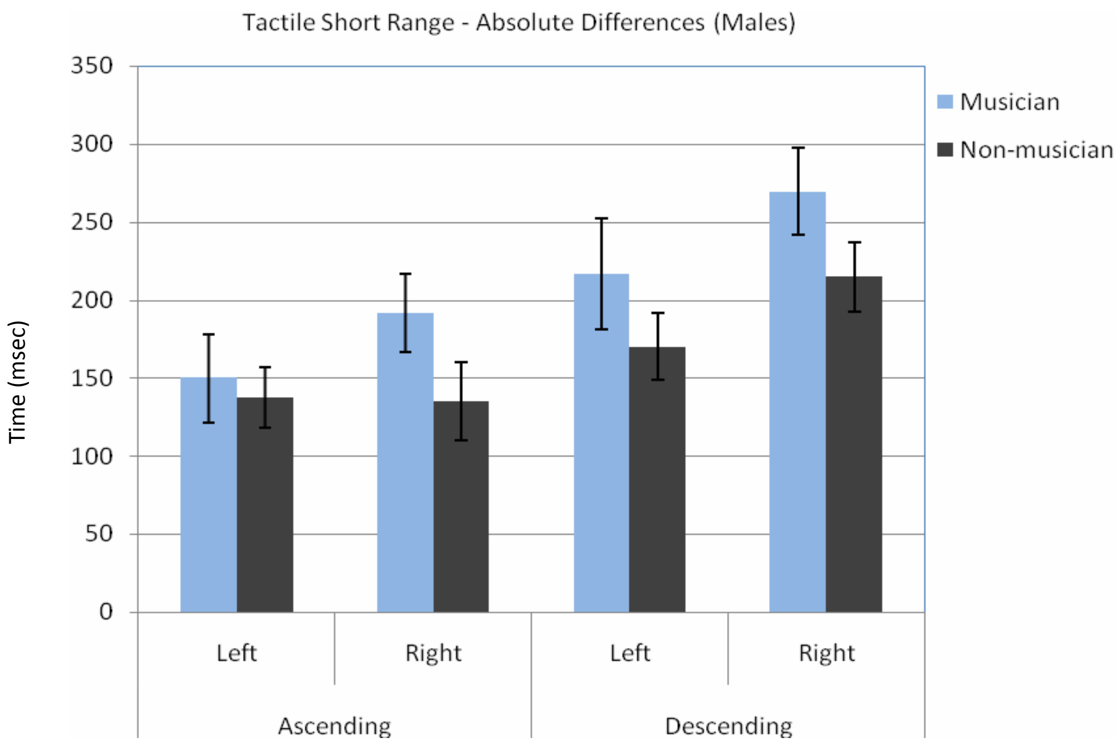

Fig. 23 The absolute difference between the male subjects' decision and the standard stimulus (500 msec.) for ascending and descending vibratory sequences.

Table 23. Absolute Differences for Short Range Tactile Ascending and Descending Order for Male Subjects

	Left	SD	Right	SD
Ascending				
Musician	150.00	84.78	191.67	76.03
Non-mus.	137.50	60.38	135.00	80.10
Descending				
Musician	216.67	107.53	269.44	83.65
Non-mus.	170.00	67.49	215.00	69.92

Fig. 24 shows the average of absolute differences for ascending and descending tactile short range sequences. The averages are given separately for the left hand and the right hand. Table 24 summarizes the average of absolute differences for ascending and descending tactile short range sequences.

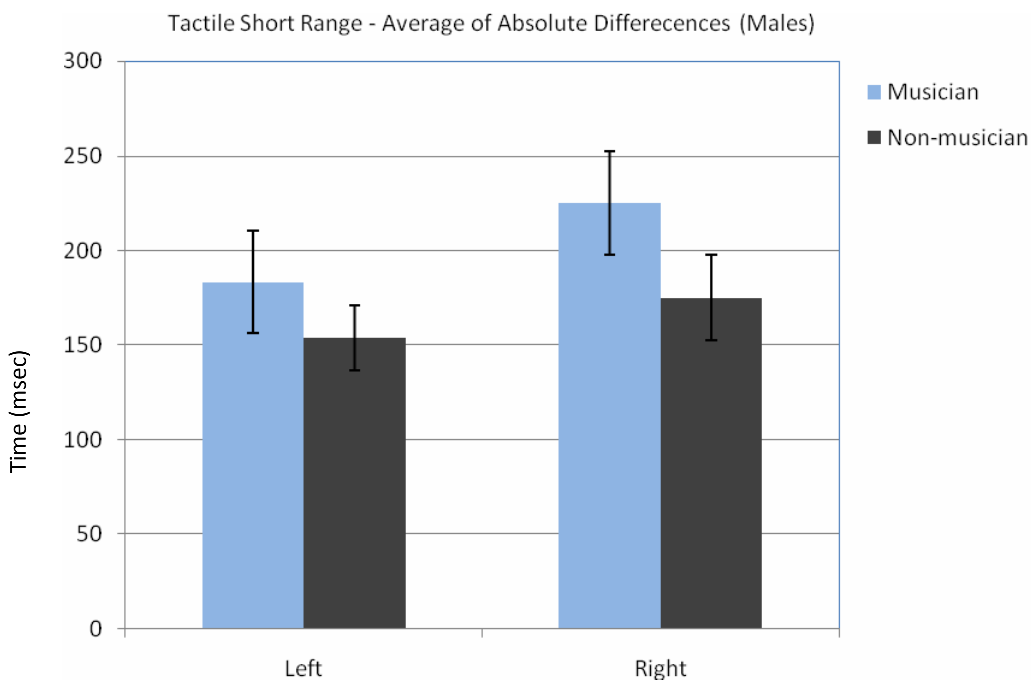

Fig. 24 The average of ascending and descending sequences' absolute difference between the male subjects' decision and the standard stimulus (500 msec.).

Table 24. The Average of the Absolute Differences for Ascending and Descending Tactile Short Range Sequences for Male Subjects

	Left	SD	Right	SD
Musician	183.33	80.53	230.56	74.51
Non-mus.	153.75	54.02	175.00	71.44

A three way ANOVA for absolute differences with repeated measures on two factors for (Group x Side x Ascending/Descending) showed that there was significant difference between musicians and non-musicians [$F(1, 68) = 4.29$, $p = 0.05$]. The absolute differences for non-musicians were smaller than the one for musicians. It also showed that there was a significant difference for ascending and descending sequences [$F(1, 68) = 10.33$, $p < 0.05$]. The absolute difference for descending order was smaller than the one for ascending order. There was significant difference between sides [$F(1, 68) = 4.29$, $p = 0.05$]. No interaction was found between the groups, hands and ascending / descending order (for group x side [F(1, 68) = 0.21, p = 0.64], for group x ascending/descending [F(1, 68) = 0.44, p = 0.50], for side x ascending/descending [F(1, 68) = 0.32, p = 0.56], for group x side x ascending/descending [F(1, 68) = 0.06, p = 0.79]).

Analyses of Percentage of Errors

Fig. 25 and Table 25 below show the percentages of errors (for the average of differences) for female musicians and non-musicians in the auditory modality. The percentages of errors were calculated according to the formula: percentage of error = ((subject's response time – standard stimulus time) / standard stimulus time) * 100.

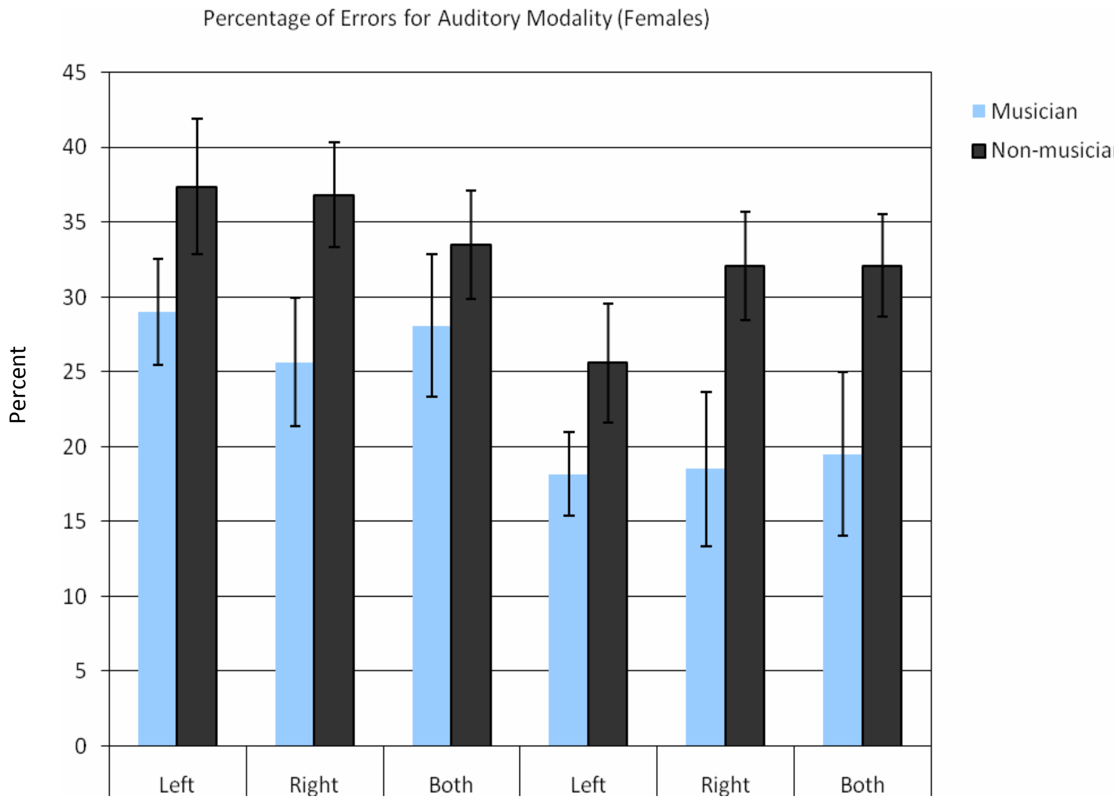

Fig. 25 Percentage of errors for auditory modality for female subjects.

Table 25. Percentage of Errors for Auditory Modality for Female Subjects

	Left.	Right	Both
Musician			
Short range	%29.01	%25.65	%28.11
Long range	%18.21	%18.53	%19.53
Non-mus.			
Short range	%37.37	%36.85	%33.5
Long range	%25.62	%32.10	%32.11

A three way ANOVA for percentages of errors with repeated measures on two factors (Group x Side x Range) for females in the auditory modality indicated a significant difference between short and long ranges [$F(1, 111) = 9.22$, $p < 0.01$]. There was less error in the long range. It also showed significant difference between musicians and non-musicians [$F(1, 111) = 16.90$, $p < 0.001$]. Musicians had less error than non-musicians. There were no significant differences between sides [$F(2, 111) = 0.01$, $p = 0.89$]. There were no significant interactions between groups, sides and ranges (for group x side [$F(2, 111) = 0.02$, $p = 0.86$], for group x range [$F(1, 111) = 0.51$, $p = 0.47$], for side x range [$F(2, 111) = 1.28$, $p = 0.26$], for group x side x range [$F(2, 111) = 0.40$, $p = 0.52$]).

Fig. 26 and Table 26 below show the percentage of errors (for the average of differences) for female musicians and non-musicians in the tactile modality.

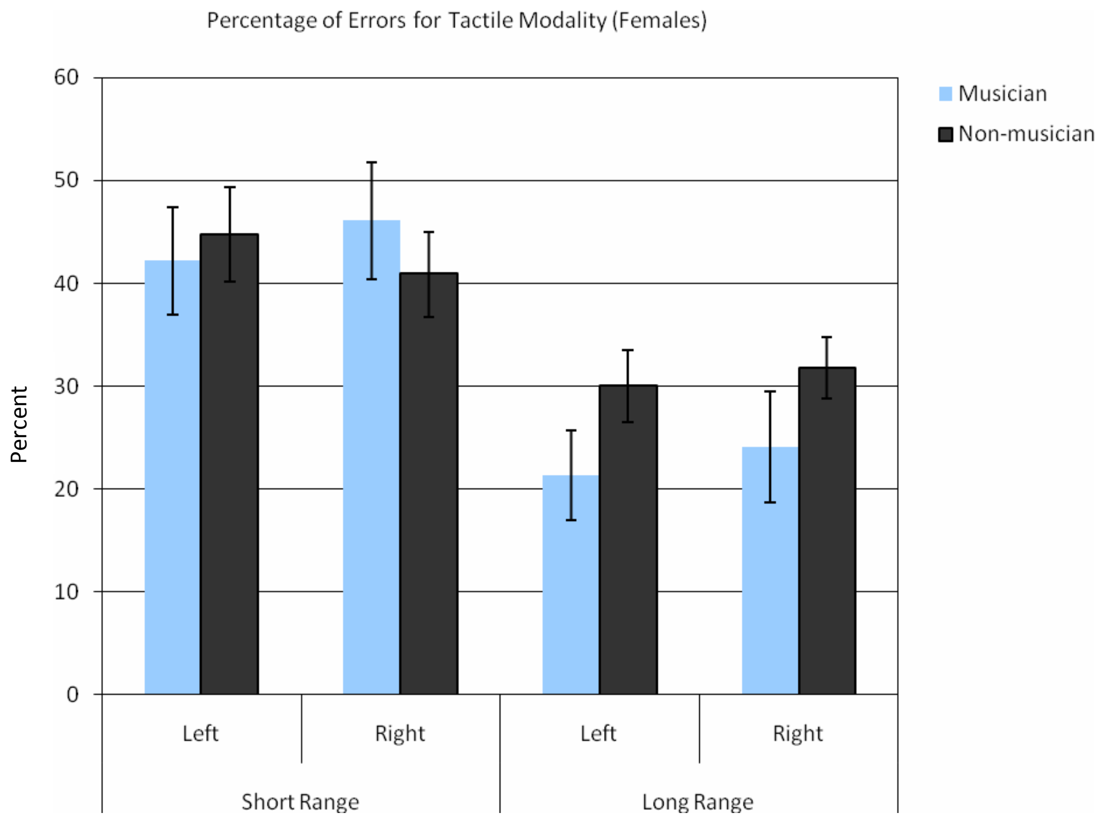

Fig. 26 Percentage of errors for tactile modality for female subjects.

Table 26. Percentage of Errors for Tactile Modality for Female Subjects

	Left.	Right
Musician		
Short range	%42.18	%46.07
Long range	%21.33	%24.10
Non-mus.		
Short range	%44.77	%40.91
Long range	%30.03	%31.78

A three way ANOVA for percentages of errors with repeated measures on two factors (Group x Side x Range) indicated a significant difference between short and long ranges [$F(1, 66) = 23.07$, $p < 0.001$]. There was less error in the long range. It showed no significant difference between musicians and non-musicians [$F(1, 66) = 2.86$, $p = 0.1$]. There were no significant differences between sides [$F(1, 66) = 0.13$,

$p = 0.71$]. There were no significant interactions between groups, sides and ranges (for group x side [$F(1, 66) = 0.91$, $p = 0.34$], for group x range [$F(1, 66) = 4.16$, $p = 0.54$], for side x range [$F(1, 66) = 0.03$, $p = 0.85$], for group x side x range [$F(1, 66) = 0.08$, $p = 0.77$]).

Fig. 27 and Table 27 below show the percentage of errors (for the average of differences) for male musicians and non-musicians in the auditory modality.

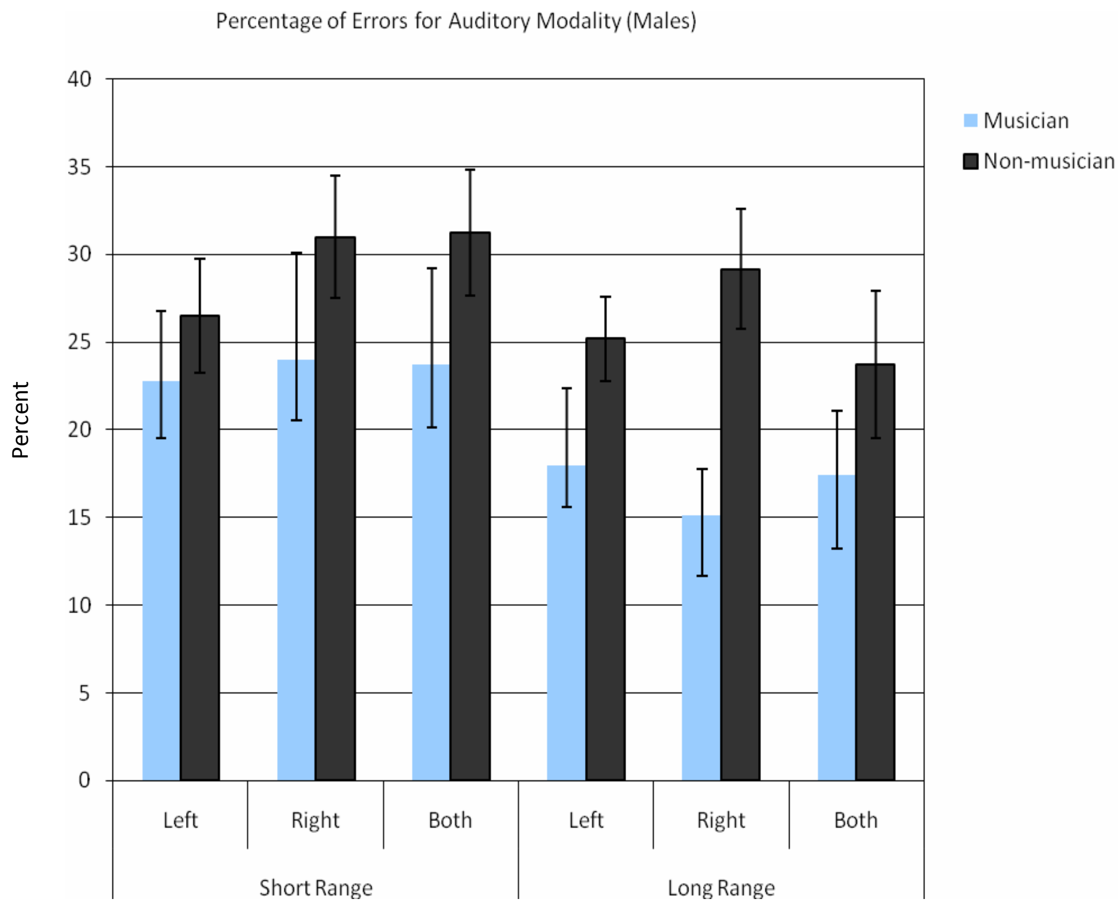

Fig. 27 Percentage of errors for auditory modality for male subjects.

Table 27. Percentage of Errors for Auditory Modality for Male Subjects

	Left.	Right	Both
Musician			
Short range	%22.78	%24.01	%23.7
Long range	%17.96	%15.10	%17.45
Non-mus.			
Short range	%26.50	%31.0	%31.25
Long range	%25.20	%29.17	%23.75

A three way ANOVA for percentages of errors with repeated measures on two factors (Group x Side x Range) indicated a significant difference between short and long ranges [$F(1, 101) = 5.50$, $p < 0.05$]. There was less error in the long range.

It also showed significant difference between musicians and non-musicians [$F(1, 101) = 12.34$, $p < 0.001$]. Musicians made less error than non-musicians. There were no significant differences between sides [$F(2, 101) = 0.14$, $p = 0.69$]. There were no significant interactions between groups, sides and ranges (for group x side [$F(2, 101) = 0.06$, $p = 0.80$], for group x range [$F(1, 101) = 0.57$, $p = 0.45$], for side x range [$F(2, 101) = 0.53$, $p = 0.47$], for group x side x range [$F(2, 101) = 0.23$, $p = 0.62$]).

Fig 28 and Table 28 below show the percentage of errors (for the average of differences) for male musicians and non-musicians in the tactile modality.

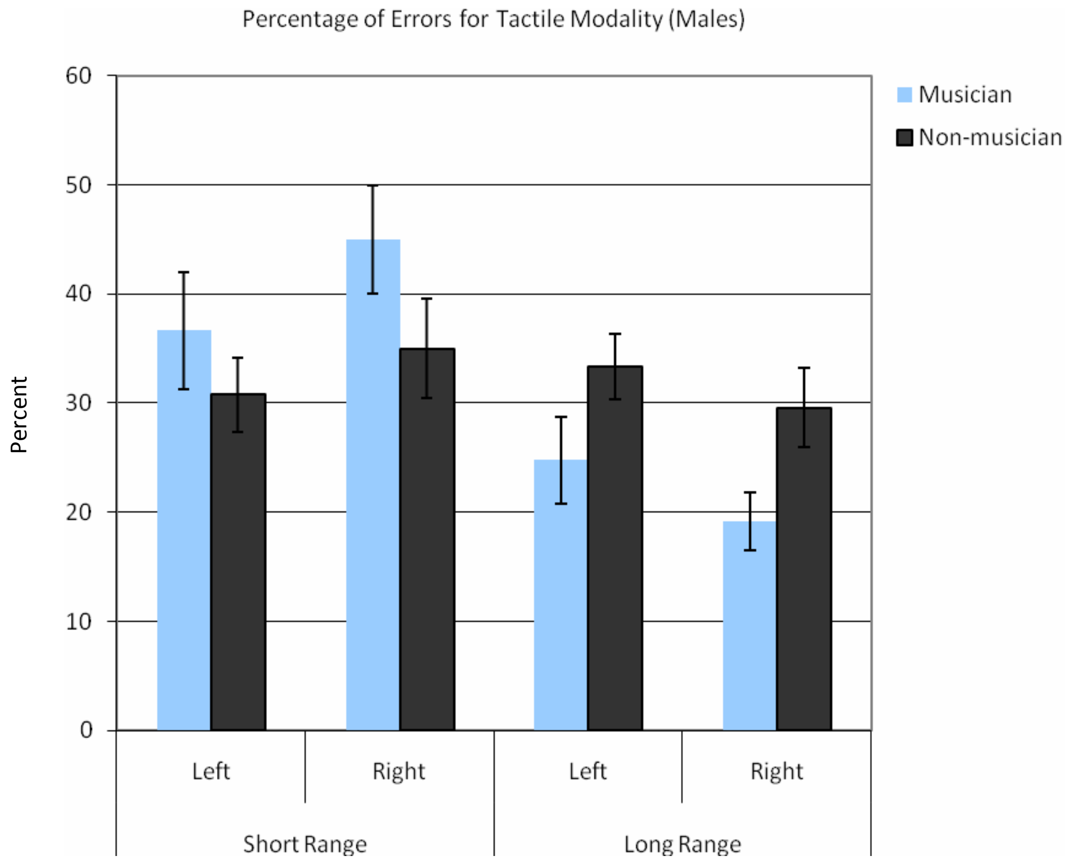

Fig. 28 Percentage of errors for tactile modality for male subjects.

Table 28. Percentage of Errors for Tactile Modality for Male Subjects

	Left.	Right
Musician		
Short range	%36.66	%45.00
Long range	%24.76	%19.14
Non-mus.		
Short range	%30.75	%35.00
Long range	%33.33	%29.58

A three way ANOVA for percentages of errors with repeated measures on two factors (Group x Side x Range) indicated a significant difference between short and long ranges [$F(1, 66) = 12.67$, $p < 0.001$]. There was less error in the long range. It showed no significant difference between musicians and non-musicians [F(1, 66) =

0.02, $p = 0.88$]. There were no significant differences between sides [$F(1, 66) = 0.30$, $p = 0.58$]. There were no significant interactions between groups, sides and ranges (for group x side [$F(1, 66) = 0.22$, $p = 0.63$], for group x range [$F(1, 66) = 0.76$, $p = 0.27$], for side x range [$F(1, 66) = 0.28$, $p = 0.74$], for group x side x range [$F(1, 66) = 0.22$, $p = 0.63$]).

CHAPTER 4

DISCUSSION

The findings in the previous chapter were mainly investigated on the basis of quantitative perspectives: absolute time estimations and absolute differences. The first one, the absolute time was the measure by which the subject thought a pair of stimuli were equal, e.g. if the absolute time was stated as 600 msec in the short time range condition for descending order, it meant that subject estimated that a signal which lasted 600 msec was equal to the standard signal that actually lasted 500 msec (the standard stimulus for the short range condition). The case was similar for the ascending order, e.g. for short range, the absolute value of 350 msec. meant that the subject thought that two signals which had durations of 500 msec (standard stimulus) and 350 msec respectively were of equal duration. On the other hand, the absolute differences were used to assess how close to the standard stimulus the subject's estimate was, e.g. for the examples above the absolute difference for 600 msec was 100 msec ($|600 - 500| = 100$) and the absolute difference for 350 msec was 150 msec ($|350 - 500| = 150$). Even though analyses of variance were calculated for absolute time estimations, this discussion is mainly based on the absolute differences' analyses of variance because they provide a better way to see how much error the subjects made compared to standard stimulus and thus providing a simpler and easier to understand measure.

Gender Differences

The results indicate significant gender differences in all modes of time estimation except in the long range tactile condition. Male subjects were better at estimating the time in long range auditory, short range auditory and short range tactile conditions.

Even though the evidence is not conclusive, there are studies which suggest that men have larger corpus callosum compared to women (Bishop & Wahlsten, 1997; Sullivan, et al., 2001). This may be one of the reasons why male subjects in the present study were generally better than female subjects in estimating time. A larger corpus callosum may lead to better and faster signal transmission from one side of the body to the contralateral hemisphere of the brain, thus to better information processing for time estimation. However, it also must be noted that there is still dispute whether the corpus callosum creates inhibitory or excitatory effects on the contralateral hemisphere (Bloom & Hynd, 2005). Another important point is that even though males are believed to have larger corpus callosum, recent findings suggest that this may not be the case (Jäncke & Steinmetz, 2003).

In addition, a meta-analytic review in which data from 4,794 female and 4,688 male subjects were examined shows that there is some small but significant difference between genders in terms of prospective time estimation when subjects are previously informed in advance that they would be making duration judgments (Block, Hancock & Zakay, 2000). Prospective time estimation was used in this study, too. This meant that subjects were informed that they were about to make time estimation judgments before the experiment started (which is in contrast with the retrospective time estimation paradigm in which subjects are asked to make time judgments after they finish the experiment; they do not know that they will be asked to estimate time beforehand). The current findings support the conclusions of the meta-analytic review by Block, et al (2000).

Effects of Music Training on Laterality

Comparisons of performances by musicians and non-musicians show significant differences between these groups (for both genders for long durations) in both modalities such that musicians have better time estimation than non-musicians. Regarding hemispheric differences, there are no significant differences except for long range tactile condition for male subjects. Male musicians in the tactile long range condition have better performances when the tactile stimulus was applied to their right hands (left hemisphere). Male non-musicians also have better performances with right hand stimulation (left hemisphere).

On the other hand, except for the long range tactile condition, no significant difference was found in terms of laterality for auditory or tactile long duration estimation. Another point is that for short auditory duration estimation, there is a significant difference between musicians and non-musicians (both male and female subjects); musicians are better than non-musicians again without any laterality difference; however for short tactile durations no such difference was found between female musicians and female non-musicians, suggesting that they have approximately similar performance profiles for short tactile durations. On the other hand, male musicians were less accurate than male non-musicians in the short tactile range.

Part of this result is compatible with the finding that somatosensory interval discriminations generalize across hemispheres (Nagarajan, et al., 1998). However, there is evidence for left hemispheric advantage for temporal processing of brief tactile stimuli in which vibrations in the range of 120 msec were used with brief gaps lasting 6 to 18 msec (Nicholls & Whelan, 1998). This also contrasts with the study which suggests that mainly right hemispheric activation is found for time interval discrimination around one second (Smith, et al., 2003). Under these circumstances, the findings of the current study suggest it is difficult to claim that there is central clock localized strictly either in the left or the right hemisphere of the brain.

Effects of Music Training on Time Estimation

Comparisons of performances by musicians and non-musicians show significant differences between these groups (for both genders for long durations) in both modalities such that musicians have better time estimation than non-musicians.

Another conclusion that may be drawn is that even though the functional and anatomical changes in the musicians' brains are presumed to be related to musical tones and not to non-musical pure sinusoidal tones (Pantev et al., 2003), it can be seen from the results that musicians had more accurate performance for "non-musical" auditory duration estimation in the form of pure sinusoidal auditory signals. The present findings suggest that the implicit time training of musicians generalize to different time ranges and even for non-musical auditory stimuli. Musicians also generalize to long tactile durations, showing better performance compared to non-musicians, but this is not the case for short tactile durations. This finding shows modality-specific time estimation (Grondin, 2003; Klapproth, 2003), at least for the short range. The reason that the musicians' performances for tactile short duration estimation were worse than their tactile long duration estimation may be related to the cognitive versus sensory timing distinction put forward by Rammsayer (2003). He states that time processing in the range of milliseconds is related to sensory (biological) timing mechanisms, whereas processing in the range of seconds is mediated by cognitive mechanisms. This means that musicians may be relying on cognitive strategies such as counting and using working memory which is a possible strategy for estimating time ranges longer than 1 second. On the other hand, neuropharmacological experiments by Rammsayer suggest that time estimation of brief intervals in the milliseconds range is beyond cognitive control and seems to be modulated mainly by dopamine activity in the basal ganglia. If that is the case, then the performance difference between short auditory and tactile duration estimations may suggest that musicians are able to transfer their cognitive time estimation skills for long range auditory time estimation to the short range auditory time estimation, but they are not able to do so for the tactile condition in which they had no training (implicit time training in the context of musical training is based on auditory, not tactile processing).

Musicians' brains undergo functional and anatomical changes because of extensive specialized training (such as enlarged left planum temporale; Ho, Cheung, & Chan, 2003), and this may lead to differences between auditory perception and somatosensory perception resulting in the findings mentioned above for short auditory and tactile duration estimation. Another example of anatomical difference between musicians and non-musicians is that there are data showing that the anterior half of corpus callosum is significantly larger in musicians compared to non-musicians (Schlaug, 2003). Similar to the performance difference between genders, bigger size of corpus callosum in the brains of musicians may account for better time estimation.

Analyses of Percentage of Errors

Percentage of error analyses also reveal important points about the performance of subjects regarding length of time ranges. Male subjects have better estimation of time than female subjects. Both genders make smaller errors in the long range auditory condition. As for the tactile range, the situation is similar; the error made for long range tactile time estimation is smaller than the short range tactile time estimation. Even though it is not possible to create a model using just two data points (short range mean percentage of error and long range mean percentage of error), there is a clear trend which shows that it is easier to do time estimations in the long range. The error analyses are also compatible with the previous analyses stated above, since they also show that male subjects made less errors compared to female subjects and musicians have better time estimation compared to non-musicians.

The reason for the difference between long and short ranges can be related to the cognitive time estimation skills which were mentioned in the previous section. In the light of distinction put forward by Rammsayer, the subjects may be relying on cognitive strategies to make temporal estimations in the seconds range which is not automatic unlike the automatic time estimation made for the ranges around the 500 msec range. If this is true, then the present studies suggest that cognitive time estimations of temporal durations are more accurate than sensory estimations.

Conclusion

The main idea of this thesis was to investigate aspects of time estimation mechanisms and assess how an extensive specialized training such as music training that requires implicit timing performance would affect timing of different durations for different modalities and hemispheres. The present study was based implicitly on the assumption that there is no single clock in the brain localized to a specific region but rather a distributed timing system emerges from the interaction of neural cell assemblies. The data presented above support this idea because there are no significant differences between the hemispheres for different durations and modalities. Another idea was that musical training would generalize across different modalities. The data support the idea that musicians were able to generalize to different modalities for the long durations but not for the short durations, their short tactile duration estimations were not significantly different from non-musicians.

To summarize the data and the results, it can be said that the first hypothesis which proposed that musicians would perform better in temporal discrimination tasks that are in the sub-second range compared to non-musicians was partially supported; musicians were better than non-musicians for short auditory time estimations. However, musicians were not better than non-musicians in the short range tactile time estimation. The results also supported the second hypothesis partially which stated that musicians would be able to generalize the temporal discrimination task to different modalities. Data showed that musicians were also better for long range tactile time estimation, however there was no significant difference for short tactile durations. Finally, the third hypothesis which stated that musicians and non-musicians would have similar performance levels for temporal discrimination tasks in the long range was not supported because significant difference was found between musicians and non-musicians for the long range time estimation, musicians were better in the long range time estimation tasks.

For further study, it may be suitable to take a more vigorous approach to the problem of time estimation mechanisms in the brain by using a wider range of temporal stimuli, and population of subjects. For example, in addition to musicians, subjects who necessarily use time estimation regularly, such as in some professional sports, can be compared with people who are not professional sports players. The methods of the experiments can be more detailed by including different standard stimuli such as 1 second, 5 second, or more. In addition to measuring the response of subjects behaviorally more sophisticated measurement techniques such as EEG, fMRI and PET can be used. Besides, different modalities such as visual modality can be used in experimental design so that different modalities can be contrasted in terms of time estimation.

REFERENCES

Belin, P., McAdams, S., Thivard, L., Smith, B., Savel, S., Zilbovicius, M., et al. (2002). The neuroanatomical substrate of sound duration discrimination. *Neuropsychologia,* 40, 1956-1964.

Bever, T. G., & Chiarello, R. (1974). Cerebral dominance in musicians and non-musicians. *Science,* 185, 537-54.

Bishop, K.M., & Wahlsten D. (1997). Sex differences in the human corpus callosum: myth or reality? *Neuroscence and Biobehavioral Reviews,* 21(5), 581-601

Block, R.A., Hancock, P.A., & Zakay, D. (2000). Sex differences in duration judgments: a meta-analytic review. *Memory and Cognition,* 28(8), 1333-46.

Bloom, J.S., Hynd, G.W. (2005). The role of the corpus callosum in interhemispheric transfer of information: excitation or inhibition? *Neuropsychology Review,* 15(2), 59-71.

Boemio, A., Fromm, S., Braun, A., & Poeppel, D. (2005). Hierarchical and asymmetric temporal sensitivity in human auditory cortices. *Nature Neuroscience*, 8, 389-395.

Buonomano, D. V. (2005). A learning rule for the emergence of stable dynamics and timing in recurrent networks. *Journal of Neurophysiology*, 94, 2275-2283.

Buonomano, D. V., & Karmakar, U. R. (2002). How do we tell time? *The Neuroscientist ,* 8(1), 42-51.

DeLacoste-Utamsing, M.C., & Holloway , R.L. (1982). Sexual dimorphism in the human corpus callosum. *Science*, 216(4553), 1431-1432.

Dolu, N., Gölgeli, A., Süer, C., Asçıoğlu, M., Özesmi, Ç., & Şahin, Ö. (2004). Sex-related differences in time estimation and the role of expectancy. *International Journal of Neuroscience*, 114(7), 805-815.

Dragoi, V., Staddon, J. E., Palmer, R. G., & Buhusi, C. V. (2003). Interval timing as an emergent learning property. *Psychological Review*, 110(1), 126-144.

Eagleman, D. M., Tse, P. U., Buonomano, D. V., Janssen, P., Nobre, A. C., & Holcombe, A. O. (2005). Time and the brain: How subjective time relates to neural time. *The Journal of Neuroscience ,* 25 (45), 10369-10371.

Elias, L. J., Bulman-Fleming, M. B., & McManus, I. C. (1999). Visual temporal asymmetries are related to asymmetries in linguistic perception. *Neuropsychologica*, 37, 1243-1249.

Gazzaniga, M., Corballis, P., & Funnel, M. (2003). Temporal discrimination in the split brain. *Brain and Cognition* (53), 218-222.

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, 84, 279-325.

Gibbon, J. & Church, R. M. (1984). Sources of variance in an information processing theory of timing. In H. Roitblat, T. G. Bever, & H. S. Terrace (Eds.), *Animal cognition* (pp. 465-488). Hillsdale, NJ: Erlbaum.

Grondin, S. (2003). Sensory modalities and temporal processing. In Helfrich, H. (Ed.), *Time and Mind II: Information Processing Perspectives*, (pp. 61-77). Hildesheim, Germany: Hogrefe & Huber Publishing.

Grondin, S. (2001). From physical time to the first and second moments of psychological time. *Psychological Bulletin*, 127(1), 22-44.

Güçlü, B., Bolanowski, S.J. (2005) Vibrotactile thresholds of the Non-Pacinian I channel: I. Methodological issues. *Somatosensory and Motor Research,* 22 (1-2), 49-56.

Halberg, F., & Cornélissen, G. (1994). Introduction to chronobiology. Retrieved June 9, 2007, from http://www.msi.umn.edu/~halberg/introd/index.html

Hellige, J. B. (2001). *Hemispheric Asymmetry: What's Right and What's Left (Perspectives in Cognitive Neuroscience).* Cambridge, Massachusetts: Harvard University Press.

Ho, Y., Cheung, M., & Chan, A.S. (2003) Music training improves verbal but not visual memory: cross-sectional and longitudinal explorations in children. *Neuropsychology*, 17(3), 439-450.

Jäncke, L., & Steinmetz, H. (2003). Anatomical brain asymmetries and their relevance for functional asymmetries. In K. Hugdahl, & R.J. Davidson (Eds.), *The Asymmetrical Brain* (187-229). Cambdridge, Massachusetts: MIT Press.

Klapproth, F. (2003). Notable results regarding temporal memory and modality. In Helfrich, H. (Ed.), *Time and Mind II: Information Processing Perspectives*, (pp. 79-96). Hillsdale, NJ: Erlbaum.

Loftus, E.F., Schooler, J.W., Boone, S.M., & Kline, D. (1986). Time went by so slowly: Overestimation of event duration by males and females. *Applied Cognitive Psychology*, 1(1), 3-13.

Masaki, M., Kashioka, H., & Campbell, N. (2002). Modeling the timing characteristics of different speaking styles. *Proceedings of 2002 IEEE Workshop on Speech Synthesis*, (pp. 63-66).

Matell, M. S., & Meck, W. H. (2000). Neuropsychological mechanisms of interval timing behaviour. *BioEssays* , 94-103.

Middlebrooks, J. C., & Greenhaw, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology*, 1, 135-159.

Nagarajan, S. S., Blake, D. T., Wright, B. A., Byl, N., & Merzenich, M. M. (1998). Practice-related improvements in somatosensory interval discrimination are temporally specific but generalize across skin location, hemisphere and modality. *The Journal of Neuroscience*, 18 (4), 1559-1570.

Nicholls, M. E. & Whelan, R. E. (1998). Hemispheric asymmetries for the temporal resolution of brief tactile stimuli. *Journal of Cilinical and Experimental Neuropsychology ,* 20(4), 445-456.

Pantev, C., Engelien A., Candia, A.V., & Elbert, T. (2003) Representational cortex in musicians. In I. Peretz, & R. Zatorre (Eds.), *The Cognitive Neuroscience of Music*, (pp. 382-395). USA: Oxford University Press.

Rammsayer, T. (2003). Sensory and cognitive mechanisms in temporal processing elucidated by a model system approach. In Helfrich, H. (Ed.), *Time and Mind II: Information Processing Perspectives*, (pp. 97-113). Hillsdale, NJ: Erlbaum.

Rietveld, W. (1996). General introduction to chronobiology. *Brazilian Journal of Medical and Biological Research ,* 29(1), 63-70.

Rubia, K., & Smith, A. (2004). The neural correlates of cognitive time management: a review. *Acta Neurobiologiae Experimentalis*, 64, 329-340.

Schlaug, G. (2003) The brain of musicians. In I. Peretz, & R. Zatorre (Eds.), *The Cognitive Neuroscience of Music*, (pp. 366-381). USA: Oxford University Press.

Smith, A., Taylor, E., Lidzba, K., & Rubia K. (2003). A right hemispheric frontocerebellar network for time discrimination of several hundreds of milliseconds. *Neuroimage*, 20(1), 344-50.

Sullivan, E.V., Rosenbloom M.J., Desmond, J.E., Pfefferbaum, A. (2001). Sex differences in corpus callosum size: relationship to age and intracranial size. *Neurobiological Aging,* 22(4), 603-11.

Wright, B. A., Buonomano, D. V., Mahncke, H. W., & Merzenich, M. M. (1997). Learning and generalization of auditory temporal-interval discrimination in humans. *The Journal of Neuroscience , 17* (10), 3956-3963.