

THE EFFECT OF HARMONIC AND INHARMONIC SOUND ON ROUGHNESS
PERCEPTION IN THE TONGUE AND FINGERTIP



DİDEM KATIRCILAR

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BY

DİDEM KATIRCILAR



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PLAGIARISM

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Date: 22.03.2022

Name/Surname: Didem KATIRCILAR

ABSTRACT

Multisensory integration refers to the integration of multiple senses by the nervous system. Auditory and tactile features are closely related senses as can be understood from the fact that adjectives such as soft, rough, and warm are used commonly for auditory and tactile features. Previous studies show that different characteristics of auditory cues may cause perceiving tactile cues as smoother or rougher. In this thesis, the effect of harmonic and inharmonic sounds on tactile roughness perception was studied by tongue and fingertip while they are presented simultaneously. We expected the participants to perceive surfaces rougher while they listen to inharmonic sounds due to auditory roughness. We presented simultaneous and sequential harmonic and inharmonic sounds with three sandpapers with different roughness levels (P100, P120, P150 grit numbers) to the participants. Results suggest that participants perceive sandpaper with the P120 grit number rougher while they listen to simultaneous inharmonic sounds than simultaneous harmonic sounds by their fingertip in two different experiments. However, any effect of harmonicity on the sandpapers with P100 and P150 grit numbers was not observed for fingertip. In addition to this, there is no effect of harmonic and inharmonic sounds on roughness perception for tongue. We suggest that auditory roughness may enhance tactile roughness perception for surfaces with particular roughness levels for fingertip, possibly when there is an ambiguity in roughness estimation.

ÖZET

Çoklu duyu entegrasyonu, sinir sistemi tarafından birden fazla duyudan gelen bilginin entegrasyonunu ifade eder. Yumuşak, sert, sıcak gibi sıfatların işitsel ve dokunsal özellikler için yaygın olarak kullanılmasından da anlaşılacağı üzere işitsel ve dokunsal duyular yakından ilişkilidir. Önceki çalışmalar, işitsel ipuçlarının farklı özelliklerinin, dokunsal ipuçlarının daha yumuşak veya daha pürüzlü olarak algılanmasına neden olabileceğini göstermektedir. Bu tezde, harmonik ve inharmonik seslerin dil ve parmak ucu ile dokunsal pürüzlülük algısına etkisi birlikte sunularak incelenmiştir. Katılımcıların işitsel pürüzlülük nedeniyle inharmonik sesleri dinlerken yüzeyleri daha pürüzlü algılamaları beklenmiştir. Farklı pürüzlülük seviyelerine (P100, P120, P150 kum sayıları) sahip üç zımpara kağıdı ile eşzamanlı ve sıralı harmonik ve inharmonik sesler katılımcılara sunulmuştur. Sonuçlar, her iki deneyde de katılımcıların eşzamanlı inharmonik sesleri dinlerken, parmak uçlarıyla eşzamanlı harmonik seslere kıyasla P120 kum numaralı yüzeyi daha pürüzlü algıladıklarını göstermektedir. Ancak parmak ucu için P100 ve P150 tane numaralı zımpara kağıtlarının harmoninin herhangi bir etkisi gözlemlenmemiştir. Bunun yanı sıra harmonik ve inharmonik seslerin dilin pürüzlülük algısına herhangi bir etkisi gözlenmemiştir. İşitsel pürüzlülüğün, pürüzlülük algısında bir belirsizlik olduğu durumda, belirli pürüzlülük seviyelerine sahip yüzeyler için dokunsal pürüzlülük algısını artırabileceği düşünülmektedir.

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1. INTRODUCTION

Perceiving our world, planning our behavior and acting accordingly could be possible by decoding and interpreting ambiguous sensory information through different sensory mechanisms such as touch, taste, smell, hearing or sight (Ernst & Bühlhoff, 2004; Fulkerson, 2013). These sensory mechanisms cannot be separated from each other, since our brain combines information from different sensory modalities to create a robust perception (Fulkerson, 2013). One of our cross-modal experiences is texture perception. When we explore a surface of an object, not only tactile cues but also visual and auditory cues help us to assess its texture properties such as roughness and slipperiness (Lederman, 1982; Bergmann Tiest, 2010). For instance, we can see the visual pattern of a surface and hear the sound that was generated by our touching while we are feeling the vibrations via fingertip (Lederman, 1982). Roughness draws most attention when it is compared to other dimensions in tactile texture perception research (Hollins et al., 2000; Klatzky & Lederman, 2010). However, although there are studies which show that different sound characteristics such as frequency and amplitude of touch-produced sounds affect tactile roughness perception (Guest et al., 2002; Klatzky & Lederman et al., 2010), there are limited studies which examine how non-touch produced affect tactile roughness perception. In addition to this, most of the studies which investigate multisensory roughness perception focus on fingertip when it is compared to oral perception (Kravchuk et al., 2012). Therefore, the aim of this thesis is to investigate the effects of harmonic and inharmonic sounds on tactile roughness perception by tongue and fingertip.

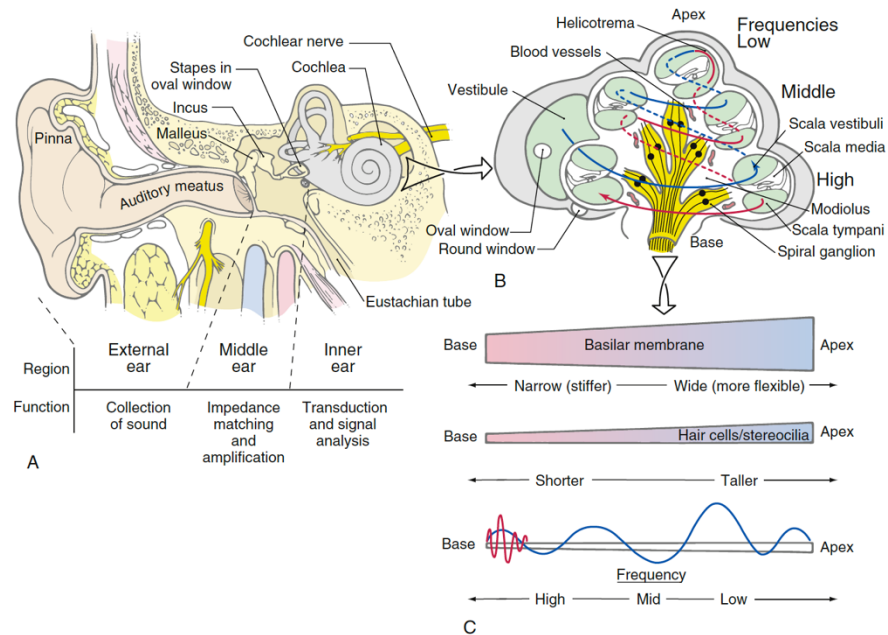
1.1. Sound Perception

1.1.1. Nature of Sound

Vibration of an object such as bird flapping wings or vibration of human vocal cord may generate air pressure which are perceived as a sound when they reach the human auditory system (Warren, 2008). Periodic vibrations are perceived as tone whereas aperiodic vibrations perceived as noise. The vibrations lead to compression and rarefaction of air molecules which creates sound waves. Sine waves which are produced by tuning fork are used to describe basic sound characteristics such as frequency, amplitude and waveform although sine wave does not exist in the nature. Frequency refers to cycles per second and it is indicated by Hertz (Hz) whereas amplitude is expressed by decibel and related to loudness. There are two different waveform which are simple and complex waveform which depends on the frequency included by the sound. Single frequency generates simple waves whereas sound has different frequencies produce complex waves (Purves et al., 2013). There are subjective qualities of a sound such as loudness, pitch and timbre which are associated with basic sound characteristics. Loudness refers to intensity of a sound which is denoted by decibel (dB). The sensitivity of human ears decreases for higher and lower frequencies while it becomes most sensitive for the frequency range from about 100 to about 5000 Hz (Purves et al., 2013). The other subjective quality of sound is pitch which has an important role on speech or music perception. Physical qualities of the sounds which are frequency and periodicity of a sound are related to pitch perception. The arrangement of pitch as sequential or simultaneous refers to melody in music or harmonicity and tonality respectively (Oxenham & Micheyl, 2013). Lastly, timbre is distinctive perceptual quality when the auditory stimuli have similar pitch and loudness qualities. Playing same note with same sound intensity through different musical instruments generate different sounds due to timbre (Purves et al., 2013).

1.1.2. Human Auditory System

Hearing is a process of perceiving acoustic world via human auditory system (Oxenham, 2018; Peterson et al., 2021). Auditory system responsible for hearing consists of peripheral structures which are outer, middle and inner ear and brain regions including cochlear nuclei, superior olivary nuclei, lateral lemniscus, inferior colliculus, medial geniculate nuclei, and auditory cortex (Peterson et al., 2021). Energy waves which move through the air molecules generate sound waves. Hearing process begins when the sound waves reach the outer ear and then they move through the eardrum where the acoustic energy is transformed into mechanical energy (Emanuel et al., 2009; Peterson et al., 2021). Then the mechanical energy travels into the middle ear to vibrate three small bones: the malleus, incus and stapes. These three bones are responsible to amplify and carry the mechanical energy to the cochlea in the inner ear through the oval window. The mechanical energy which receives inner ear vibrates the basilar membrane within the hair cells which is also called stereocilia. One of the responsibilities of basilar membrane and hair cells is converting vibration into neural information (Purves et al., 2008). Besides this, the basilar membrane also plays a crucial role on encoding frequencies of sound stimuli. Different regions on the basilar membrane are activated based on sound frequency. Stiffer portions of basilar membrane which are located near the oval window are activated by high frequencies whereas compliant portions respond to low frequencies (Purves et al., 2013). This organization of the sound frequencies in cochlea is named as tonotopic gradient (Peterson et al., 2021) (Figure 1).

Figure 1*Human Auditory System*

Note. Henkel, C.K. (2018). Fundamental Neuroscience for Basic and Clinical Applications ||
 The Auditory System

Information which comes from peripheral auditory system follow parallel pathways through the central auditory system. Inferior colliculus plays a crucial role on interaction between auditory information from the cochlear nucleus and motor system to guide motor actions in line with the auditory information. The interaction of auditory signals which comes from two ears takes place at the superior olivary complex. Auditory signals from the cochlear nucleus also convey the information to the nucleus of the lateral lemniscus which is crucial for the sound localization ability. After auditory information are processed in the different region in the brain stem, it reaches thalamus which is the last station before primary auditory cortex (Purves et al., 2013).

Auditory cortex consists of the primary auditory cortex and secondary auditory cortex. Primary auditory cortex receives a major part of the projections from thalamus and process low-level sensory information whereas the secondary auditory cortex is responsible for high-level auditory processing such as word recognition or speech comprehension (Purves et al., 2013). People are capable of perceiving, interpreting and understanding environmental sounds via the human auditory system.

1.1.3. Harmonicity Perception and Sequential or Concurrent Sound Discrimination

Most of the sounds that we hear in our daily life are harmonic or quasi-harmonic. Harmonic sounds consist of integer multiples of fundamental frequency (F_0) which is the lowest frequency in the sound. For instance, if 100 Hz is the fundamental frequency of a sound; its first harmonic is 200 Hz, second harmonic is 300 Hz and so on determined by nature of the sound. Even when the sound does not include this fundamental frequency or F_0 is masked in the sound, complex harmonic tones create a sensation of a pitch which refers to F_0 (Micheyl & Oxenham, 2010). Harmonic sounds were studied with two different presentation type as sequential and simultaneous in the literature. Micheyl and Oxenham (2010) claim that the auditory system shows greater tendency to group simultaneous sounds which have harmonic relationships. Besides this, Borchert et al. (2011) indicate that when people are asked to detect F_0 differences between two pair of tones, they show better performance to compare fundamental frequencies in simultaneously presented sounds than sequentially presented sounds. This also shows that listeners use different cues to distinguish F_0 . For instance, when sounds are presented sequentially; each tone elicits a sensation of pitch and it makes the comparison difficult due to timbre differences. However, if sounds are presented simultaneously, listeners rely on overall sensations which are elicited by the same and different

F0 pairs for the comparison (Micheyl & Oxenham, 2010). Demany and Semal (1990) also indicated that different neural mechanisms may be involved to compare pitch in simultaneously and sequentially presented sounds.

Harmonic sounds are transformed into inharmonic sounds by adding a constant value.

For instance, if the harmonic sound consists of harmonic series such as 100 Hz, 200 Hz, 300 Hz, 400 Hz; adding a constant value (e.g. 30 Hz) convert it into inharmonic series such as 130 Hz, 230 Hz, 330 Hz and 430 Hz. Inharmonic sounds have uncertain periodicity, fluctuating frequencies and ambiguity of pitch. This lack of harmonic relations in sound creates a roughness sensation (Schneider & Frierler, 2008).

Most of the research which investigate neural pathway of harmonicity detection focused on simultaneous harmonic sounds. When acoustic information has different F0 and is perceived as mistuned, a conflict arises between the perceived frequencies and expected frequencies. This information conveys to higher order brain areas to detect the existence of multiple auditory sources (Alain & Tremblay, 2007). Mistuned harmonic also elicits negative waves on the frontocentral scalp 150 ms after sound onset. This is called object-related negativity (ORN) due to participants' tendency to report existence of two concurrent objects (Alain et al., 2001).

Attention does not have an impact on amplitude and latency of ERPs. This shows that conscious process is not involved in the sound segregation process in simultaneously presented sounds (Alain et al., 2001).

Frequency separation also was studied with sequential sounds. For instance, A and B has different frequencies and represent different tones. An MEG study which presents two tones as ABA to the participants shows that P1, N1, P2 responses elicit when participants detect two streams rather than one stream. In addition to that, participants also give response when the

sound stimuli alter one stream condition to two stream condition and vice versa. Results show that P1, N1, P2 responses indicates not only frequency discrimination but also perceptual state of participants (Gutschalk et al., 2004). In addition to this study, participants were presented sounds with ABA_ patterns in two different conditions. In one condition they ignore the auditory stimulus and watch a silent movie whereas they choose if they heard two or one stream and participate in the task actively. Ignoring the stimulus causes decreased positive activity that elicit during ABA_ repetitions. This shows that attention plays an important role when the sound is related to each other perceptually although they are not temporally congruent (Alain & Tremblay, 2007).

Although these previous studies give information how our brain process frequencies presented simultaneously or sequentially, which brain areas are responsible for harmonically related and sequentially or simultaneously presented frequencies needs further investigation.

1.2. Human Somatosensory System and Tactile Perception

Human somatosensory system can provide information about different features of an objects such as dryness, temperature, size, surface and texture. There are mechanoreceptors, thermoreceptors and nociceptors which are responsible for processing tactile information by somatosensory system (Feher, 2012). Mechanoreceptors in skin play a crucial role on feeling of touch, pressure and vibration during somatosensory processing (Møller, 2003). There are different kinds of mechanoreceptors located in human skin: The Pacinian corpuscles, Meissner's corpuscles, Merkel's disk and Ruffini corpuscles. All of these receptors have myelinated axons which provide quick detection of stimulus by the central nervous system (CNS). Pacinian corpuscles react to vibration whereas Meissner's corpuscles are also involved in processing of vibration. However, Meissner's corpuscles react to lower frequencies than

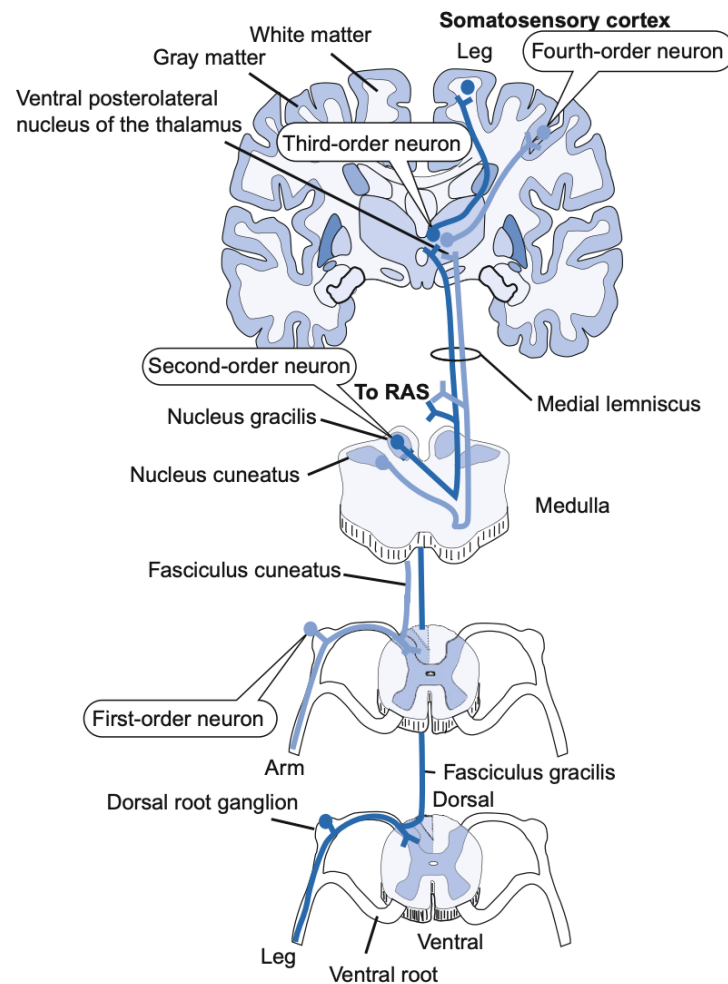
Pacinian corpuscles. Merkel's disc is essential for perceiving stable touch pressure on the skin with its small receptor field while Ruffini's corpuscles respond to push and pull of the skin by other body parts with its large receptive field. Ruffini's corpuscles also take part in processing proprioceptive information and pressure sense on the skin. These mechanoreceptors are divided into two groups as rapidly adapting (RA) which consists of Pacinian corpuscles Meissner's corpuscles and slowly adapting (SA) which includes Merkel's disc and Ruffini's corpuscles (Feher, 2012). Rapidly adapting receptors fire quickly after the stimulus onset but decrease during ongoing stimulation. Slowly adapting receptors continue to fire during the stimulation (Purves et al., 2001). There are two different thermoreceptors as cold and warm receptors. They are responsible for responding to stimuli in line with the temperature changes. In addition to mechanoreceptors and thermoreceptors, nociceptors are also crucial for tactile perception. Mostly noxious stimulation such as damage on the skin leads to nociceptor activation (Hendry & Hsiao, 2013).

Information obtained from mechanoreceptors project into brain through the dorsal column pathway to create a tactile perception. There are nerve endings located in the skin or near the skin and cell bodies in the dorsal root ganglia. First order neurons which are also called primary afferent neurons are the first neurons fired by environmental stimuli. First order neurons carry the sensory information throughout tracts of axons in the dorsal root of the spinal cord. Dorsal column has two parts: fasciculus cuneatus and fasciculus gracilis (Feher, 2012). They are connected with the nucleus cuneatus and nucleus gracilis in the medulla. Nucleus cuneatus receives information from the upper part of the body whereas nucleus gracilis receives information from the lower part of the body. The neurons located in the nucleus gracilis and nucleus cuneatus are called second order neurons and convey the information throughout the

opposite side of the medulla and then thalamus. Thalamus organizes the third-order neurons that carry sensory information to the primary somatosensory cortex. Fourth order neurons are responsible to process carried information in the primary somatosensory cortex (Feher, 2012) (Figure 2).

Figure 2

Somatosensory Pathway

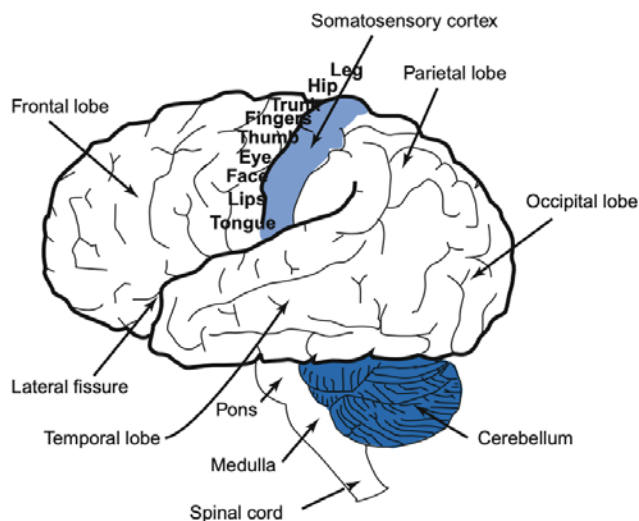


Note. Feher, J. (2012). Cutaneous Sensory Systems. Quantitative Human Physiology.

Primary somatosensory cortex resides in the parietal lobe and process the somatosensory input. It has a topological arrangement which is protected while carrying the information from the skin to the cerebral cortex. (Feher, 2012) (Figure 3). Somatosensory representation in primary sensory cortex indicates the amount of cortical area which is responsible to process somatosensory information from different body parts in line with the amount of the information which comes from that specific area. Homunculus which is also called “little man” shows the body representation of primary somatosensory cortex with the “food to tongue” pattern which is from medial to lateral axis (Figure 4) (Warren et al., 2013).

Figure 3

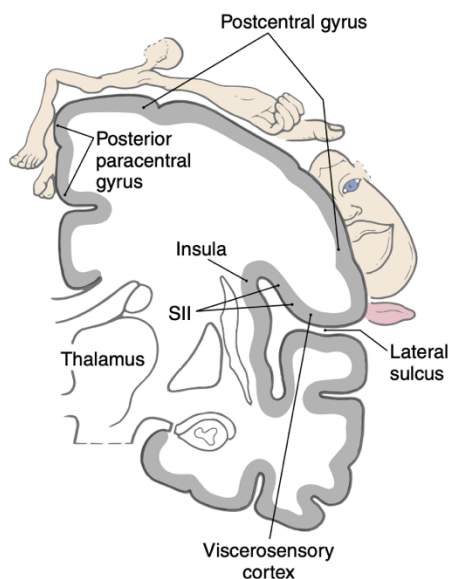
The brain map of somatosensory cortex



Note. Feher, J. (2012). Cutaneous Sensory Systems. Quantitative Human Physiology.

Figure 4

Homunculus or the “little man”



Note. Warren, S., Capra, N. F., & Yeziarski, R. P. (2013). *The Somatosensory System I. Fundamental Neuroscience for Basic and Clinical Applications.*

The axons of nociceptors and thermoreceptors do not carry the information throughout the dorsal root. The information gained from thermoreceptors and nociceptors go through the anterolateral or ventrolateral tract, then thalamus and cerebral cortex (Feher, 2012).

After the somatosensory information is processed in primary somatosensory cortex, relevant brain areas such as adjacent brain areas and secondary somatosensory cortex get involved in the tactile perception process. Then limbic structures such as amygdala and hippocampus receive the information especially for emotional responses and memory (Purves et al., 2013).

Density of receptors and size of receptive field play a crucial role on tactile acuity.

Glabrous skin has greater density of receptors when it is compared to other body regions such as the back. Besides this, the receptive field implies the area of the skin which has cutaneous

receptors. Some body parts have small receptive fields with high density of receptors whereas the other body parts have large receptive fields with low density of receptors. Small receptive field with high density is better at detecting small differences than a large receptive field with low density (Warren et al., 2013).

In respect of sensitivity of tongue and fingertip, both of them are highly innervated body parts with high sensitivity. However, mechanisms of tongue perception have not been described as well as fingertips. High sensitivity of fingertips contributes to the process of perceiving object properties in the external world, whereas tongue has the same role in perception of the object (food) properties in the mouth with its high sensitivity as well. Since they have a similar role in tactile perception, comparison of oral tissues with fingertip mechanisms can help us to understand better underlying mechanisms of oral perception (Miles et al., 2018).

1.2.1. Tactile Roughness Perception with Fingertip

Texture perception is an important part of our life which has an impact on our choices in daily life such as clothes and furniture (Engelen & de Vijk, 2012). Touching an object provides different information about its texture properties such as roughness and slipperiness (Bergmann Tiest, 2010). Most of the texture perception studies focus on roughness when it is compared to other texture properties (Hollins et al., 2000; Klatzky & Lederman, 2010).

Because roughness is the most distinctive feature of a texture which is perceived by touch (Bergmann Tiest & Kappers, 2006). People can assess the roughness of a surface by rubbing their finger on it (Altinsoy, 2008) since one can intuitively feel the texture properties of an object touching it (Suzuishi et al., 2020).

Although physical explanation of the roughness is height differences on the surface, there

is no well-defined explanation of the roughness for perception since it may vary by the stimuli used. However, touching a rough surface creates irregular pressure distribution and vibration on the skin generally (Bergmann Tiest, 2010). Pressure and vibration are crucial to discriminate sandpapers by static and dynamic touch for specific roughness levels. Hollins & Risner's study (2000) indicates that fine surfaces which have particle size under 100 μm are difficult to discriminate by only static touch since vibration cues are needed to assess it. However, coarser surfaces which have greater particle size more than 100 μm can be discriminated by only static or dynamic touch. Therefore, vibration is an important part of roughness perception for finer surfaces which have smaller particle size than 100 μm (Hollins & Risner, 2000).

Connor et al., (1990) compared psychophysical judgments of humans and neurological response of monkeys on the same set of stimuli in respect of roughness perception since these two species have similar neural mechanisms for tactile perception. Their results showed that perceived roughness has been associated with neural activation in the brain. Higher roughness level of a surface may lead to higher variation occurring on skin and therefore, higher variation of the firing rate for related receptors (Connor et al., 1990). Slowly adapting nerves play a crucial role on perception of coarse surfaces since there is stronger correlation between magnitude estimation and variance of slowly adapting nerves when compared to rapidly adapting nerves (Hsiao et al., 1993). Pacinian system also essential for finer textures which has smaller particle size than 200 μm since neural codes of vibration intensity were coded with this system to perceive roughness of finer surfaces (Hollins & Bensmaia, 2007; Hollins & Bensmaia, 2005). As a result, there are different factors which affect how roughness of the surfaces are perceived. However, in general, two main channels contribute to the roughness

perception: vibration for finer surfaces and spatial variance for coarser surfaces (Bergmann Tiest, 2010).

1.2.1.1. Practical Applications of Texture and Roughness Perception

How people perceive the texture of surfaces is an important question in product design. Product experience of consumers is affected by sensory properties of the product (Hengfeng Zuo et al., 2016). For instance, Barnes et al. (2004) investigated how rubbing fingertips on a variety of surface roughness affects desirability when people think these surfaces will be used in cosmetics' packaging. In addition to that, Hengfeng Zuo et al. (2016) examined how material textures and their combination play a role on its beauty, value and also consumers' overall preference. Authors claimed that perceiving a product as comfortable depends on its texture to be smooth, warm and non-sticky for the case of hair dryer, which is used as a product in their research study. Feelings elicited by different material properties are crucial for material selection (Hengfeng Zuo et al., 2016). In addition to product design, roughness perception also plays an important role on tactile perception of fabrics. Texture properties of a fabric can evoke feelings about fabric products (Mooneghi et al., 2014). Roughness or smoothness of a fabric also has an impact on comfort of clothes whereas it also affects buying decisions of consumers (Sisodia & Parmar, 2019). Lastly, architectural designers also use surface roughness while designing a place in order to satisfy customers' needs (Rosen et al., 2016).

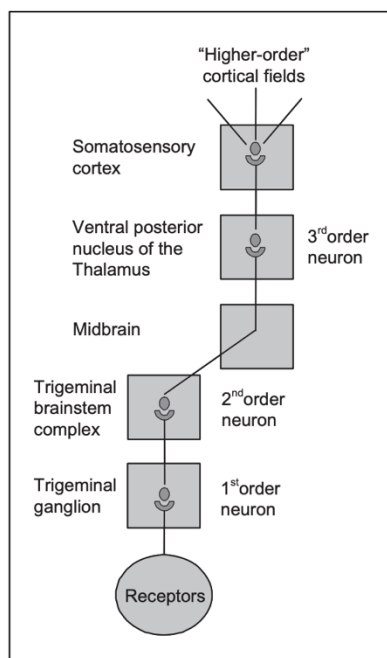
1.2.2. Oral Roughness Perception with Tongue

The most sensitive organ of the human body is the mouth (Engelen & van der Bilt, 2008) since it is one of the most innervated body areas with nerve fibers and receptors (Mountcastle, 1974). Therefore, it has great sensitivity for tactile stimulation (Van Boven & Johnson, 1994) and better discrimination performance when compared to most of the body parts (Engelen &

van der Bilt, 2008). Discrimination threshold is lowest in the tip of tongue and in the hard palate in the oral cavity (Ringel & Ewanowski, 1965). Somatosensory receptors such as mechanoreceptors, nociceptors and thermoreceptors are responsible for transmitting relative information. There are three mechanoreceptors that are found in the mouth and lips which are slowly adapting type I and II (SAI and SAII) and rapidly adapting type I. Orofacial region does not have rapidly adapting type II (RAII) although it is found in hand (Johansson et al., 1988). Tongue is innervated by primarily rapidly adapting nerves (Trullson & Johansson, 2002) which can detect changes fastly in the application and removal phases of the stimuli (Trullson & Essick, 2010). In addition to slowly adapting and rapidly adapting nerves, tongue also has a deep tongue receptor which has a larger receptive field located in the muscle (Trullson and Essick 1997).

Figure 5

Trigeminal somatosensory system



Note. Engelen, L., & van der Bilt, A. (2008). Oral Physiology and Texture Perception of Semisolids. *Journal of Texture Studies*.

Transmitting information from oral regions to the central nervous system is provided by trigeminal somatosensory system as oral regions consist of trigeminal nerves. Oral somatosensory receptors create action potential after stimulation. First order sensory neurons transmit the information to trigeminal ganglia and then second order sensory neurons convey it throughout the trigeminal brainstem complex. Trigeminal brainstem complex consists of two parts which are the principal nucleus and the spinal nucleus. The principal nucleus processes information from mechanoreceptors whereas the spinal nucleus processes the information from nociceptors and thermoreceptors. After midbrain, third order neurons carry the information to the ventral posterior nucleus of thalamus and then to the somatosensory cortex. Higher order cortical areas receive relevant information from the somatosensory cortex to create tactile perception (Figure 5) (Engelen & van der Bilt, 2008).

Most of the information regarding roughness perception of tongue were obtained from studies comparing tongue and hand, while focusing on the latter (Bukowska et al., 2010). Linne et al.'s (2017) study which investigated individual differences in lingual tactile roughness perception showed that people can differentiate surface roughness even with a small difference ($0.023\ \mu\text{m}$). Brisben et al. (1999) also showed that people can distinguish vibratory amplitudes smaller than $0.01\ \mu\text{m}$ via glabrous skin of hand. However, using different methods and stimuli cause variance while comparing tongue and fingertip (Miles et al., 2018). For this reason, Miles et al. (2018) conducted a research study to examine roughness discrimination with fine surfaces in terms of tongue and fingertip. Participants were presented with stainless steel coupons which have varied roughness levels between 0.177 and $0.465\ \mu\text{m}$. It was found that the tongue

condition revealed a better performance in roughness discrimination task with significantly lower just noticeable difference than fingertip.

1.2.2.1. Roughness Perception with Tongue in Food Science

Texture has a determining impact on sensory acceptance and rejection for foods since people have an expectation about the texture of the foods. If our expectations are satisfied, then we consider the aroma and taste of the food. However, in other cases, i.e. if the texture expectations are not met with the real texture, it may cause rejection of food. For instance, when there is sand in the spinach, its texture can be a reason for rejection and aversion of the food. There is no specific texture type for acceptance or rejection since it depends on the food (Chen & Engelen, 2012).

Particle size of a food has a crucial impact on the roughness perception of foods.

Strongest perception of roughness was obtained when particle size was around 80–140 mm where also hard particles create rougher sensation than soft particles (Engelen & van der Bilt, 2008). Friction is an important factor for roughness perception whereas high friction leads to rougher sensation and vice versa (Engelen & van der Bilt, 2008; Prinz & de Wijk 2005). Oral tissue perceives the friction immediately with the movement of the food (de Wijk & Prinz, 2006).

However, people do not prefer rough texture for soft products such as dairy desserts. The preferred texture properties of these types of foods are smoothness, slipperiness and creaminess. Adding more particles affects the perception of these foods negatively. The reason for this could be high sensitivity of the mouth to the small particles (Engelen & van der Bilt, 2008).

Besides this, food texture is not only important for food acceptance but it is also because they are preferred due to being perceived as healthier. For instance, vegetables which have a rough and hard structure are perceived as healthier and have low calories when compared to smooth and creamy foods. The results of these studies may affect the strategy of the food industry (Biswas et al., 2014). For example, Burger King's lower-calorie fries have a rougher surface than regular higher-calorie fries (Strom, 2013). Biswal et al. (2014) claimed that oral haptic has an impact on perception of Burger King fries which have rougher texture as healthier.

1.3. Multisensory Integration and Cross-modal Interaction

Our cognitive capacity allows us to process more than one kind of sensory information while perceiving external events (Stevenson et al., 2014). This information from different sensory modalities may be combined in our brain to create a robust perception (Ernst & Di Luca, 2011). This process is called 'multisensory integration'. In some cases, the information from one sensory modality may also affect the salience of the stimulus from another sensory modality, which corresponds to 'cross - modal interaction' (Spence, 2011). Combined sensory inputs may create a 'unitary perception' in multisensory integration whereas altering the salience of sensory stimuli may improve or impair the perception in cross-modal interaction (Stein & Stanford, 2008).

There are three principles which are used to explain multisensory integration: spatial rule, temporal rule and the principle of inverse effectiveness (PoIE) (Holmes, 2009). When sensory stimuli from different sensory modalities are spatially congruent, it leads to multisensory integration to be stronger. Similarly, temporal coincidence of stimuli also creates

the same effect (King & Palmer, 1985). According to the principle of inverse effectiveness, weaker unisensory stimuli result in more effective multisensory integration (Holmes, 2009). There are neuroimaging and electrophysiological studies investigating whether cross-modal processing and multisensory integration take place in low-level or high-level brain areas (Xu et al., 2020). Although previous research had indicated that high-level brain areas such as the superior temporal sulcus or posterior parietal cortex (PPC) are responsible for sensory interactions (Yau et al., 2015), later research on low-level brain areas such as primary sensory cortices (Ghazanfar et al., 2005; Lakatos et al., 2007), brainstem (Koehler et al., 2011) or thalamus (Komura et al., 2005; Bieler et al., 2018) showed that cross modal processing already occurs at early stages. As far as audio-tactile interaction is concerned, the caudomedial auditory association cortex is involved in both somatosensory and auditory processing. Together, these results show that multisensory integration may take place at the early level of auditory cortical processing for both auditory and somatosensory sensory inputs (Schroeder et al., 2001). Tactile, somatosensory and auditory systems are also considered as associated systems due to the frequency-based neural codes of these two modalities (Ro et al., 2013 & Butler et al., 2012). Superior temporal gyrus as well as parietal and temporal regions in general are parts of the brain where auditory and somatosensory inputs are combined (Foxe et al., 2002, Pérez-Bellido et al., 2018).

1.3.1. Cross-modal Audio-tactile Mapping and Roughness Perception

How sensory information from different sensory modalities are combined or affected by each other has drawn researchers' interest over a quarter century (Spence, 2011). Cross-modal correspondences between sensory modalities and their underlying mechanisms have been studied with synaesthetic and non-synaesthetic individuals (Etzi et al., 2016). Various

terms such as ‘natural cross-modal mappings’ (Evans & Treisman, 2010), ‘synaesthetic correspondences’ (Melara & O’Brien, 1987), ‘synesthetic associations’ (Parise and Spence, 2008), ‘cross-modal associations’ (Martino & Marks, 2001) address the same phenomenon of the tendency of the brain to create an association between different sensory modalities through a sensory feature (Spence, 2011). In this paper, the term ‘cross-modal correspondence’ will be used to indicate this phenomenon which is more appropriate to address its neuronal underlying mechanisms (Spence, 2011).

One of the earliest and most famous studies in cross-modal correspondence (Köhler, 1929) indicates the association between non-words Baluma/Takate and rounded/angular shapes respectively. According to participants’ reports, non-word Baluma was matched with the rounded shapes whereas non-word Takate was matched with the angular shapes over the chance level. After Köhler’s study, this phenomenon was also studied with ‘Bouba and Kiki’ non-words and ‘angular and rounded shapes’ by Ramachandran and Hubbard (2001). They explained this correspondence between visual and auditory modalities with the adjacent brain areas which may be involved in the processing of visual outline of the shapes and shape of the lips during the pronunciation of the vowels (Ramachandran & Hubbard, 2001). Similarities during information processing may lead to structural mediated cross-modal correspondence (Spence, 2011). Both adjacent brain areas may be involved in the process of stimulus feature (Ramachandran & Hubbard, 2001) or stimulus intensity (without considering sensory modality) may lead to increased neuronal activity in the brain (Spence, 2011). For instance, size may be processed in the same way as loudness in our brain since both of them are related to magnitude (Deroy et al., 2013). Besides visual and auditory modalities as in the Bouba and Kiki, there is a strong relationship between auditory and tactile modalities (e.g. tone and tactile sense) in terms

of terminology which is used to describe stimulus features such as ‘rough’, ‘sharp’, ‘soft’ or ‘warm’ (Gunther & O’Modhrain, 2003). The association between a tone and tactile senses may arise from its cortical underlying mechanisms according to both psychophysics or neurophysiological studies (Eitan & Rothschild, 2010). Interaction between auditory and tactile modalities may appear in ways such that touching could be facilitated by an auditory cue (Jousmäki, & Hari, 2006) or the sound characteristics such as frequency of the auditory cue may alter the tactile perception (Jousmaki & Hari, 1998; Lederman & Klatzky, 1999). Because auditory and tactile systems have frequency-based coding mechanisms which may cause strong association between these sensory systems (Ro et al., 2009). For instance, Jousmaki and Hari (1998) changed the frequencies and amplitudes of the sounds of rubbing palms together. This study showed that people are likely to report higher smoothness and dryness when they are subjected to sounds with higher frequencies and amplitudes and vice versa. Similarly, Guest et al. (2002) indicated that people judge abrasive surfaces to be rougher when they are subjected to sounds with higher frequencies. Not only behavioral studies, but also neuroimaging studies reveal that common brain areas may be involved both auditory and tactile information processing such as auditory cortex involved in processing of tactile cue as well as auditory cue (Schroeder et al., 2001; Schürmann, 2006). Besides these, different sound characteristics such as loudness and pitch may have a metaphoric map onto tactile senses and can be perceived as rough (Eitan & Rothschild, 2010). Bouba and Kiki phenomenon also applied to the tactile modality which indicates that sharp-transient sounds of non-words are related to rougher surfaces whereas rounded-shaped sounds are associated with the rougher texture (Etzi et al., 2016). Although these examples reveal the metaphorical associations between auditory and tactile modalities (e.g. louder sounds named as rough), when auditory and tactile stimuli

are simultaneously presented, louder sounds are also matched with the rougher textures (Peeva et al., 2004). Similarly, auditory roughness of the sound (e.g harmonisation, consonance and dissonance) may affect roughness of the visual stimuli (Liew et al., 2017; Giannos et al., 2021). Not only behavioral studies, but also neuroimaging studies reveal that common brain areas may be involved in both auditory and tactile information processing. For instance, the auditory cortex is involved in the processing of tactile cues as well as auditory cues (Schroeder et al., 2001; Schürmann, 2006). Many studies try to explain the shared brain mechanisms that play a role in audio-tactile perception, yet there is not much research directly looking into audio-tactile cross-modal correspondence based on basic auditory qualities and the underlying mechanisms compared to studies that investigate audio-visual cross-modal mapping (Eitan & Rothchild, 2010).

Semantically-mediated correspondence can also lead to an association between two different sensory modalities, aside from similar structural mechanisms. Semantically mediated cross-modal correspondence refers to using common linguistic terms to define stimulus features from different sensory modalities. For instance, “low” and “high” are the common words that are used to describe the pitch in auditory stimuli and also the elevation in the visual stimuli. In general, a higher pitch is related to higher elevations in the space and congruence of high pitch and high elevation (vs. low pitch-low elevation) lead to faster response than incongruency condition (low pitch and high elevation and vice versa) in speeded-classification tasks (Evans & Treisman, 2010). As in the example visual elevation and pitch, “rough” is an adjective that is used to describe sound features in music and also indicates a connection between tactile and auditory modalities (Gunther & O’Modhrain, 2003). Osgood’s Semantic Differential (SD) experiments may also provide an explanation to the audio-tactile mapping in

terms of semantically-mediated cross-modal correspondence. In the Semantic Differential experiment that uses factor analysis, participants rated different objects by using auditory and tactile antonyms such as loud-soft, bass-treble and hard-soft, rough-smooth respectively on a bipolar scale. Three main independent factors were used to analyze adjective ratings: evaluation (e.g good or bad), potency (e.g strong-weak) and activity (e.g fast-slow). They found out that auditory antonyms such as loud-soft or bass-treble are strongly related to potency factor as well as the tactile antonyms such as hard-soft and smooth-rough (Osgood et al., 1957). Size in vision and loudness in audition may be processed by using the same brain mechanisms since they are related to magnitude (Deroy et al., 2013). This explanation could be relevant with the Osgood's et al. (1957)'s SD technique. Because adjectives that have a strong correlation with power or potency may activate the same neurons during the process. Therefore, semantically and structurally mediated cross-modal correspondences may have an impact on audiotactile crossmodal correspondence together for roughness perception.

All these studies clearly demonstrate that there is an audio-tactile cross-modal correspondence regarding 'roughness' in two modalities. Similarities in the semantic meaning and similarities in the processing of the sensory feature may result in cross-modal correspondence between auditory and tactile modalities in terms of roughness. In the light of previous findings, we investigated how people obtain auditory information from harmonic and inharmonic sounds produced simultaneously or sequentially (similar to chord and arpeggio) and how these sounds affect tactile roughness perception. A previous study shows that inharmonic tones are perceived rough (Carroll, 1970). Therefore, we hypothesized that participants would perceive surfaces to be rougher while they are listening to inharmonic sounds compared to harmonic sounds since auditory roughness is expected to enhance tactile

roughness perception due to audio-tactile cross-modal correspondence. Moreover, we expected to observe a stronger effect of audio-tactile interaction in simultaneously presented harmonic and inharmonic sounds than sequentially presented sounds. This is because sound waves, including simple ratio frequencies, are resolved better in the subcortical auditory system when they are presented simultaneously (Tramo et al., 2001, Bidelman and Heinz, 2011) whereas sequentially presented sounds are stored and maintained in working memory and require higher-level categorization (Tezcan-Semerici, 2020).

1.3.2. Cross-modal Audio-tactile Mappings and Oral Perception

During food consumption, chemoreceptors on our tongue help us to perceive taste of the food. However, the odor of the food, its texture, color and form of the food have an impact on our perception as well (Simner et al., 2010). Cross-modal correspondence between sensory modalities also play a crucial role on food perception (Lowe et al., 2018).

Sound has three main dimension such as harmonicity, pitch and amplitude (Volkman et al., 1937). Crisinel and Spence (2010) and Simner et al. (2010) demonstrated that cross-modal correspondences between sound and taste dimensions are matched, such as higher pitch being associated with sweet and sour tastes. Besides this, background sound also leads to perceiving foods more bitter and sweet while listening to low or high pitch sounds respectively (Crisinel et al., 2012). When compared to taste and sound associations, there are limited studies which focus on cross-modal correspondence for texture (e.g roughness) and sound characteristics. Zampini and Spence (2004) found out that sound which is generated by biting can alter perception of “crispness” which is used to describe texture of a food. Sounds with high frequency and high volumes cause perceiving potato chips crispier and vice versa (Zampini & Spence, 2004). In addition to this, pseudo-chewing sound may result in perceiving food’s

texture rougher (Endo et al., 2017) since chewing sound also gives cues about texture properties of the food (Spence, 2015). Not only sound which is produced by chewing or biting but also the background noise such as white noise may influence food perception (Woods et al., 2011). Participants perceived the food crunchier when they presented noisy sounds than less noisy sounds. However, the flavor of food such as saltiness or sweetness which are not associated with the sound was not affected by background noise (Woods et al., 2011). However how different kinds of sounds affect specifically oral roughness perception is still an open question.

1.4. Aim of Experiment 1

In the light of previous findings, we investigated how people obtain auditory information from harmonic and inharmonic sounds produced simultaneously or sequentially (similar to chord and arpeggio) and how these sounds affect tactile roughness perception. Research shows that inharmonic tones are perceived to be rough (Carroll, 1970). Therefore, we hypothesized that participants would perceive surfaces to be rougher while they are listening to inharmonic sounds compared to harmonic sounds since auditory roughness is expected to enhance tactile roughness perception due to cross-modal audio-tactile interaction. Moreover, we expected to observe a stronger effect of audio-tactile interaction in simultaneously presented harmonic and inharmonic sounds than sequentially presented sounds. This is because sound waves, including simple ratio frequencies, are resolved better in the subcortical auditory system when they are presented simultaneously (Tramo et al., 2001, Bidelman and Heinz, 2011) whereas sequentially presented sounds are stored and maintained in working memory and require higher-level categorization (Tezcan-Semerici, 2020).

1.4. Aim of Experiment 2

This study aims to compare roughness perception for the tongue and the fingertip by using the same tactile stimuli since there are limited studies which compare tongue and fingertip roughness perception by using the same method and same set of stimuli. We expect that participants will show better discrimination performance with their tongue than their fingertip due to greater sensitivity of the tongue (Miles et al., 2018). In addition to this, we also examine harmonic and inharmonic sound effects on roughness while participants are using their fingertip and tongue. Because previous findings showed that there would be association between different sound characteristics and texture perception of tongue/fingertip. In Experiment 1, we claimed that cross-modal correspondence in terms of roughness perception for fingertip may occur during early sensory processing. However, since tactile information from fingertip and tongue follow different somatosensory pathways (dorsal column pathway for fingertip and trigeminal pathway for tongue); it is an open question whether there is a cross-modal correspondence for tongue in terms of roughness. We hypothesized that participants will perceive surfaces rougher in inharmonic sound condition than harmonic sound condition due to auditory roughness by their tongue and fingertip. Because the result of Experiment 1 showed that participants perceive sandpaper with 120 grit-number rougher when they listened to inharmonic sound than harmonic sound.

2. EXPERIMENT 1

2.1. Participants

40 healthy participants with an age range of 18-34 (39 right-handed, 19 female, mean age: 24.375, SD=4.505) volunteered in the experiment. They did not report any loss of sense in their tactile and auditory abilities and also did not have professional music history. Each participant

provided written informed consent. This experiment was approved by Yeditepe University Ethical Committee for Social Sciences and was in compliance with the WMA Declaration of Helsinki.

2.2. Stimuli

2.2.1. Auditory Stimuli

Eight different sound stimuli were used in this experiment. Four of these stimuli were harmonic sounds and the other four were inharmonic sounds. Every sound consisted of three frequencies. Two harmonic sounds were generated by using A3 and A4 notes as fundamental frequencies and their first and second harmonics respectively. The inharmonic version of harmonic sounds was generated by adding a constant amount (30 Hz) to all frequencies since inharmonic sounds are constituted by adding a constant frequency value to the harmonic sound frequencies to study harmonicity in psychoacoustics (Schneider & Frieler, 2008). Harmonic and inharmonic sounds were separated into two groups as sequential and simultaneous harmonic and inharmonic sounds. Simultaneous and sequential harmonic and inharmonic sounds were generated by using the same frequencies (see Table 1) and they were equally long (6 seconds). Simultaneous sounds were created by overlapping all the frequencies while sequential sounds were generated by adding all the frequencies one after the other without any temporal spacing between the frequencies. Both sequential and simultaneous harmonic and inharmonic sounds were presented to the participants. VoceVista Pro was used to create sounds with specific frequencies and the piano effect was used. Sequential and simultaneous sounds were arranged by using Audacity.

Table 1

Sound Frequencies of Experiment 1 (Hz)

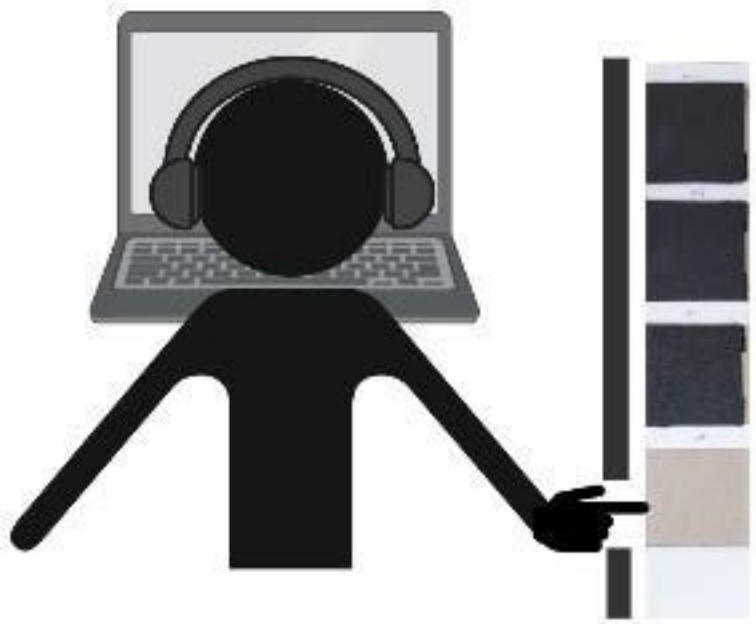
	Harmonic	Inharmonic
Sequential	130.8 – 261.6 – 392.4	160.8 – 291.6 – 422.4
Sequential	220 – 440 – 660	250 – 470 – 690
Simultaneous	130.8 – 261.6 – 392.4	160.8 – 291.6 – 422.4
Simultaneous	220 – 440 – 660	250 – 470 – 690

2.2.2. Tactile Stimuli

Waterproof silicon carbide sandpapers with three different grit numbers (P100, P120, P150, from roughest to smoothest respectively) and a surface made of PVC (polyvinyl chloride) were used as tactile stimuli. All surfaces were 8 x 8 cm. Sandpapers and a PVC surface were placed on a board (See Figure 6). Grit numbers were based on the Federation of European Producers of Abrasive Products (FEPA) P-grading system.

Figure 6

Experimental Setup



2.3. Procedure

All participants sat on a chair and stretched their arms through a hole on the standing screen to touch surfaces. They received all their instructions from the screen. Auditory stimuli were presented by headphones (Sony ZX110NC). Standing screen was used to prevent visual cues. Participants were asked to touch the surface when the auditory stimuli began and stop touching the surface when the auditory stimuli ended. All participants touched the surfaces by moving the fingertip of their dominant hand in the left-right direction. In addition to this, there was a control condition in which three sandpapers were presented without any auditory stimuli for only one time. In this condition, participants started to touch when they heard a beep sound and they continued their exploration until they heard a second beep. They kept their headphones on to block sounds that are generated by touching. In both experimental and control conditions, they touched the surfaces for 6 seconds. Participants rated the surface roughness on a scale between 1 (from smooth) 9 (to rough). In addition to that, after participants touched sandpapers three times, they were subsequently asked to touch a PVC surface for 5 seconds to prevent habituation to sandpaper. Participants had to rate only sandpapers and not the PVC surface during the experiment. They used numbers on the computer keyboard to rate the surface roughness in 5 seconds after every touch. Participants were presented with a fixation point between every trial to give time to the experimenter to prepare the next surface in 5 seconds.

Participants were asked to stabilize their speed and pressure for each trial while they were moving their fingertip on the surface to make sure that they explored each surface in the same way. After every two participants, surface materials were replaced to make sure that they do not get flattened due to repeated touching.

Every harmonic and inharmonic sound was matched with a particular type of surface

exactly once in the experiment. A surface was presented 8 times in total. The presentation of the surfaces was pseudorandomized in 27 trials (24 sandpaper presentations in sound condition, 3 sandpaper presentations in no sound condition, with extra 8 PVC surface presentations after every three trials where no response was collected).

2.4. Statistical Analysis

Roughness rating scores of each participant on 27 trials were transformed into Z-score to standardize each participant's score relative to their own distribution (Brinker, 2002) and to minimize the effects of different rating strategies (Raw data of participants' ratings from 1 to 9 could be found in Appendix A). Friedman test which is a non-parametric alternative of One-Way Repeated Measure Anova was used since the data was not normally distributed based on Shapiro-Wilk test for normality test results at alpha level 0.05. For post-hoc analysis, we performed a Wilcoxon signed rank test to compare differences among conditions. Effect size for each pairwise Wilcoxon signed-rank test was also reported (r ; $r = Z/\sqrt{n}$). We conducted these statistical analyses by using Statistical Package for Social Sciences (SPSS) at alpha level 0.05.

We also performed the Wilcoxon Signed Rank test to compare the roughness scores of the three surface types between with-sound and no-sound conditions in order to test whether the presence of sound —regardless of characteristics— alters roughness perception. This analysis was performed by JASP.

2.5. Results

Friedman test results revealed that harmonicity had a significant effect on perceived roughness ($p = .009$, $\chi^2 = 6.737$, $df = 1$). It also revealed that presentation type (simultaneous, sequential) has a statistically significant effect on perceived roughness ($p = .039$, $\chi^2 = 4.272$,

df = 1). Wilcoxon Signed-rank post-hoc test showed that participants perceived the surface rougher while they were listening to simultaneous inharmonic sounds ($Md = .584$, $n = 80$) than simultaneous harmonic sounds ($Md = .054$, $n = 80$) for sandpaper with P120 grit number, showing a moderate effect size ($Z = -3.062$; $p = .002$, $r = 0.34$). However, there was no statistically significant difference for sandpapers with 150 grit number and sandpapers with 100 grit number in terms of harmonicity (see Figure 7 and Table 2)

Figure 7

Participant ratings for harmonic and inharmonic sound conditions for all sandpaper types.

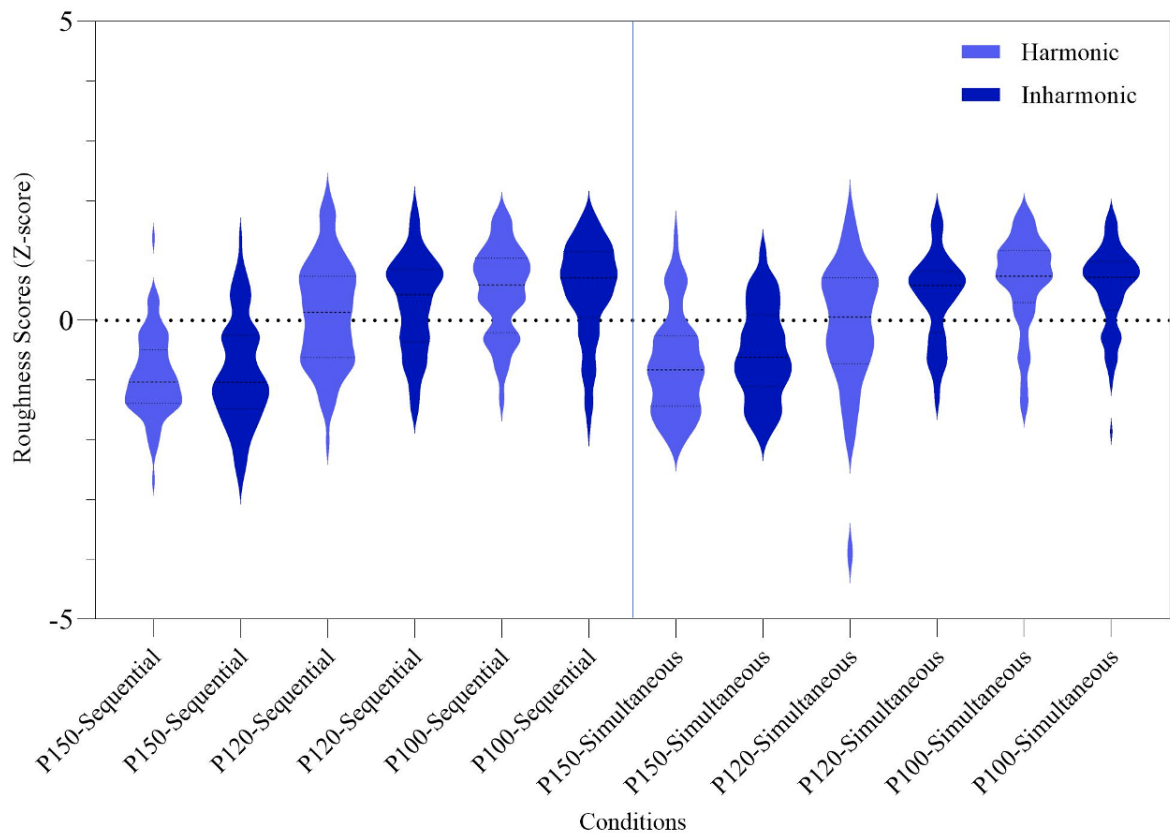


Table 2

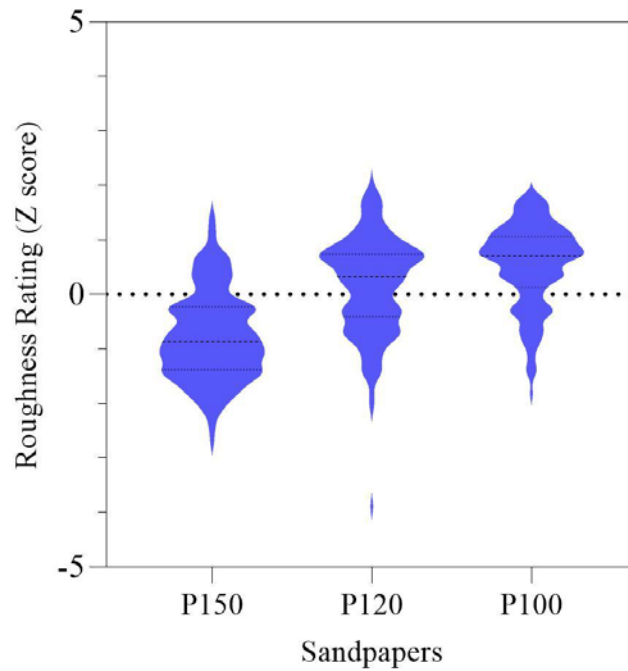
Median values of harmonic and inharmonic sound conditions for Experiment 1.

Harmonicity	Presentation Type	Surface	Median	N
Harmonic	Sequential	P150	-1.031	80
		P120	.136	80
		P100	.593	80
	Simultaneous	P150	-.826	80
		P120	.054	80
		P100	.783	80
Inharmonic	Sequential	P150	-1.035	80
		P120	.426	80
		P100	.714	80
	Simultaneous	P150	-.618	80
		P120	.584	80
		P100	.716	80

Moreover, surface type also had significant effect on perceived roughness by based on Friedman test results ($p = .000$, $\chi^2 = 272.335$ $df = 2$). Wilcoxon signed-rank post-hoc tests indicated that participants could discriminate sandpaper with P150 grit number ($Md = -.865$, $n = 320$) from sandpaper with P120 grit number ($Md = .328$, $n = 320$) ($Z = -11.551$; $p = .000$, $r = 0.64$), and from sandpaper with P100 grit number ($Md = .716$, $n = 320$) ($Z = -13.050$; $p = .000$, $r = 0.72$), sandpaper with P120 grit number number ($Md = .328$, $n = 320$) from sandpaper with P100 grit number ($Md = .716$, $n = 320$) ($Z = -5.095$; $p = .000$, $r = 0.28$) in sound conditions (see Figure 8).

Figure 8

Participant roughness ratings for the sandpapers with P150, P120 and P100 grit numbers during with-sound conditions.



Wilcoxon-signed rank test results showed that perceived roughness is higher in no-sound condition than with-sound conditions for sandpaper with P150 grit numbers ($V = 1077.000$, $p < .001$). For sandpaper with P120 grit number, perceived roughness was higher in with-sound conditions than no sound condition ($V = 39466.000$, $p < .001$). There was no statistically significant difference between no-sound and with-sound conditions for sandpaper with P100 grit number ($V = 23151.000$, $p = .127$).

2.6. Discussion

We examined how harmonicity of the sound affects our tactile roughness perception in

this study. Results demonstrate that low-level sound characteristics of the auditory stimuli such as harmonicity can affect tactile roughness perception. We expected that inharmonic sounds — which are described to have auditory roughness— to make surfaces appear rougher compared to harmonic sounds. As expected, participants could discriminate between smooth, medium and rough surfaces in with-sound conditions. Moreover, they perceived the surface with P120 grits which has medium level roughness among our sandpapers significantly rougher, when they listened to simultaneous inharmonic sounds rather than simultaneous harmonic sounds.

However, there is no statistically significant difference in roughness perception for sandpapers with P100 and P150 grit numbers. Although further research is required to explain why the auditory roughness affects the perceived surface roughness for only the sandpaper with P120 grit number, the ambiguity which occurs due to being the middle option may have increased multisensory integration, representing a similar paradigm as in Heron et al.'s study (2004). It is likely that participants relied on tactile input while deciding the roughness of the surface with P150 and P100 grit numbers. However, participants may tend to integrate other available sensory stimuli when faced with ambiguous tactile stimuli in order to create a robust perception (Ernst & Bühlhoff, 2004; Murai & Yotsumoto, 2018).

Given that the participants were not aware of how many surface types were presented, extreme roughness for sandpaper with 100 grit number and extreme smoothness for sandpaper with 150 grit number may have served as landmarks to the two ends for determining maximum and minimum ratings and led the rating of the middle roughness level more vulnerable to cross modal effects. Chimata and Schwartz (2018) and Simoes-Franklin (2011) showed that when participants were presented with three surfaces having different roughness levels, their discrimination performance is better for roughest and smoothest ones when it compared to

middle option. As indicated in Heron's et al.'s (2004) study, when the stimulus has higher certainty (e.g. smoothest and roughest sandpaper in this study), the effect of alternative sources on perceptual output may relatively decrease. In their study, when uncertainty increased for visual position, vulnerability of perceived position to be affected by auditory stimuli also increases. Similarly, perceptual ambiguity might have led to perceived roughness to be affected by harmonicity in our study for the sandpaper with medium roughness level.

Moreover, Parncutt and Hair (2011) claimed that frequencies that can not be separated easily are related to auditory roughness which could be exemplified as rubbing your fingertip on a sandpaper. Auditory and tactile roughness have common features and evoke similar feelings for individuals. Moreover, smoother surfaces were perceived to be more pleasant while rougher surfaces were assessed as more unpleasant (Etzi et al., 2014), which is the same for sound preference. Inharmonic sounds are less preferred compared to harmonic sounds because people prefer consonance over dissonance (McDermott et al., 2010). Literature shows that pleasantness of the stimuli or their cognitive meaning may establish abstract relationships between them which lead to cross-modal correspondence (Crisinel & Spence, 2010). Furthermore, as Spence (2011) has suggested, some common —amodal— stimulus features between different sensory modalities (such as roughness in this study) may enhance the possibility of multisensory integration (Frings & Spence, 2010; Radeau & Bertelson, 1987; Thomas, 1941; Spence, 2007). Therefore, our findings also support that the abstract relationship between auditory and tactile stimuli in terms of roughness may also contribute to the audio-tactile interaction process for material perception. These findings also comply with the cross-modal correspondence between taste and music. The reasons for association between

sounds and tastes are the pleasantness of these stimuli, their emotional valence and textural similarities between them (Guetta & Loui, 2017).

In addition to abstract relationships, perceptual similarities during information processing may cause ‘weak synesthesia,’ which is also specified as ‘cross-modal correspondence’ (Spence & Deroy, 2013). Common frequency channels between auditory and tactile sensory modalities in our brain (Yau et al., 2009) corroborate results that show similarities between auditory and tactile sensory processing. Further neuroimaging research is needed to understand how the brain processes frequency information obtained from harmonicity and surfaces.

Our study and others studies (Jousmaki & Hari, 1998; Guest et al., 2002, Yau et al. 2009) showed that there are crucial similarities between auditory and tactile sensory modalities in how their frequencies are processed by the brain. This brings up a new question: at which stage of information processing do these modalities interact and their featural information such as frequency is processed by the brain? (Butler et al., 2012). There are electrophysiological, neuroimaging, and anatomic tracing studies in humans and monkeys which demonstrate that auditory and somatosensory inputs interact in early sensory processing. It is also important to point out that even if higher-order multisensory integrative areas are damaged, the ability of multisensory integration can be still preserved (Foxy & Schroeder, 2005). Although these studies draw attention to feedforward processing and early sensory interactions, other studies showed that sensory inputs may be processed independently by unimodal sensory systems. More specifically, feature-level information is independently extracted by these systems and later on combined in higher-order multisensory areas (Calvert et al., 1998; Driver and Noesselt, 2008). The electrophysiological study of Butler et al. (2012) shows that multisensory integration of auditory and tactile frequency information occurs in early sensory processing

mechanisms preattentively to create frequency representation together. To investigate the same question with respect to audio-tactile roughness perception, our participants were presented with sequential and simultaneous harmonic and inharmonic sounds. According to our results, the interaction between auditory and tactile sensory inputs for roughness perception takes place in early processing due to the requirement of higher-level processing to perceive sequential harmonic and inharmonic sounds. However, this view needs to be supported with electrophysiological studies specifically for roughness perception.

Only three different roughness levels were used in this study which makes it difficult to generalize our results to all roughness levels that we encounter in our daily life. The same question should be investigated by using fine surfaces as well. Besides this, our harmonic sounds include fundamental frequency and its harmonics. However, consonant and dissonant sounds may have similar effects as harmonic and inharmonic sounds on tactile roughness perception. Consonant sounds are periodic just like harmonic sounds while dissonant sounds are perceived to be rough just like inharmonic sounds (Bidelman & Heinz, 2011). Western tonal music can be used in further studies to examine the effects of auditory roughness on tactile roughness perception since consonant and dissonant sounds in Western tonal music have similar effects as harmonic and inharmonic sounds.

No sound condition affected roughness perception of surface types differently. While smooth surfaces were perceived rougher when there was no sound, medium surfaces were perceived smoother. We suspect that roughness perception of the smooth surfaces were confounded by the fact that this condition was presented as the first stimulus in the experiment, without any training session. This may cause the rating of smooth sandpaper to be higher. Since the roughness rating of medium surfaces relies on sound types and is prone to be perceived

rougher with inharmonic sounds, mean roughness rating of the no-sound condition is already expected to be lower.

To summarize, our study shows that frequency representations in both auditory and tactile modalities could be dependent on their early-level interactions for roughness perception. In addition to this, our results also indicate that harmonicity of the sound and auditory roughness may have a cross-modal correspondence with tactile roughness perception. These findings might be useful for architectural design practices, which have started considering the auditory and tactile modalities as well as the visual modality in recent years (Spence, 2020). Moreover, these results can be used for multisensory product design because people may construct an idea about the tactile properties of a product without touching it, like from auditory information (Spence & Zampini, 2006).

3. EXPERIMENT 2

3.1. Participants

30 healthy participants (19 females and 10 males) with an age range of 18-35 ($M=23.86$, $SD=3.95$) volunteered in this study. They did not report any loss of their sense of touch and hearing and also did not have professional music history. In addition to this, all participants were asked not to eat or drink anything except water 1 hour before the experiment. This experiment was approved by the Yeditepe University Ethical Committee for Social Sciences and was in compliance with the WMA Declaration of Helsinki.

3.2. Stimuli

3.2.1. Auditory Stimuli

Six different auditory stimuli were used in this experiment. Six auditory stimuli were divided into two categories as three harmonic and three inharmonic sounds. Every sound

consisted of three frequencies. Harmonic sounds were created by using fundamental frequencies which correspond to C3, A3 and F3 notes in the piano and their first and second harmonics (See Table 3). A constant value (30 Hz) was added to all frequencies in the harmonic sounds to generate inharmonic versions of harmonic sounds (Schneider & Frieler, 2008). Each frequency was generated by using VoceVista Software and piano effects were applied to the frequencies by adding an overtone to every frequency. Audacity Software was used to combine frequencies and create the final version of the sounds. Duration of every sound was 3 seconds.

Table 3
Sound Frequencies of Experiment 2 (Hz)

Harmonic	Inharmonic
130.8 – 261.6 – 392.4	160.8 – 291.6 – 422.4
174.6 – 346.2 – 523.8	204.6 – 376.2 – 553.8
220 – 440 – 660	250 – 470 – 690

3.2.2. Tactile Stimuli

Three different sandpapers (waterproof silicon carbide) with P150, P120, P100 grit numbers (higher grit numbers indicate lower roughness level) and a surface made of PVC (polyvinyl chloride) were used as tactile stimuli for both fingertip and tongue session. Higher grit numbers correspond to smoother surfaces.

Surfaces for fingertip session were 6 cm x 6 cm whereas surfaces which are 5 cm in length and 2 cm in width were placed on the abeslang for tongue session. The Federation of European

Producers of Abrasive Products (FEPA) P-grading system was considered for grit numbers and particle size (micron grade).

3.3. Procedure

3.3.1. Fingertip Session

Participants sat on a chair and placed their arms in a suitable position to use the standing screen between the computer and surfaces. The angle between their arms and body was approximately 90 degrees. All the instructions were presented to the participants through the screen. Sennheiser 350BT Bluetooth 5.0 headphones were used to present harmonic and inharmonic sounds during the experiment. Visual cues were eliminated by using a standing screen. Participants were instructed to explore surfaces with the index finger of their dominant hand in the right-left direction while harmonic and inharmonic sounds were presented at the same time. Then they were asked to rate surface roughness from 1 (smooth) to 9 (rough). There was also a control condition that participants received no sound but were asked to rate surface roughness. In the control condition, a beep sound was used to start and end the surface exploration. They continued to wear headphones in control condition to prevent touch produced sounds. In sound and no sound conditions, they explored the surfaces for 3 seconds. After every three trials which required touching the sandpapers, they were asked to touch surfaces made of PVC for 3 seconds as well to avoid habituation to the surfaces, although they did not rate this PVC surface.

There was a training session before the experiment started in order to make participants familiar with the roughness level of the surfaces. In the training session, participants explored the sandpaper with 120 grit number two times in total in sound and no sound conditions.

All participants were asked to keep the velocity of their hand/finger movement at the same level during the experiment to ensure they explored all surfaces similarly. Surfaces were renewed after every two participants.

Every harmonic and inharmonic sound was presented with a particular type of surface exactly once in the experiment. A surface was presented 6 times in total. They were presented with the surfaces and harmonic and inharmonic sounds in a pseudorandomized order with 27 trials (18 sandpaper presentation in sound condition, 9 sandpaper presentation in no sound condition, with extra 8 PVC surface presentation after every three trials where no response was collected).

3.3.2. Tongue Session

Participants were presented with surfaces attached to abeslangs. Instructions were presented through headphones except the ‘rate’ instruction since they closed their eyes while they touched the surfaces. All of the participants were asked to stabilize the velocity of their hand and their tongue during the touch session to prevent any differences depending on this. In addition to this, they touched the surfaces by moving the abeslang from right to left on their tongue as in the fingertip session. Before the experiment, participants were asked to bring the abeslang in front of their mouth to be prepared touching right after ‘Close your eyes’ instruction and bring it back to the standing screen right after the ‘Open your eyes’ instruction.

They closed their eyes when they were presented with ‘close your eyes’ instruction. Then, in sound condition, they started touching the stimuli when the sound started and stopped touching when the sound ended. In control (no sound) condition, they started touching the stimuli when they received ‘touch’ instruction via headphone and stopped touching when ‘stop’ instruction was given via headphone as well. After touching, they received ‘open your eyes’

instruction and right after they brought back the abeslang to behind the standing screen. Then they rated the surface roughness by using numbers on the computer keyboard from 1 to 9. They were presented with a PVC surface after every three stimuli with the sandpapers in order to minimize habituation effect as in the fingertip session. There were fixation point presentations for 3 seconds between every trial to give enough time to the experimenter for preparing and presenting the surfaces.

Fingertip and tongue session was counterbalanced to prevent effect of modality on perceived roughness and pseudorandomized order was the same for the tongue and the fingertip session.

3.4. Statistical Analysis

Z score transformation was applied to data to prevent effect of different rating strategies (Brinker, 2002) and to be able to compare the possible different rating intervals of the two modalities (i.e. tongue and fingertip) (Raw data of participants' ratings from 1 to 9 could be found in Appendix A for both tongue and fingertip conditions). Since data were not normally distributed (according to the Shapiro-Wilk test at 0.05 alpha level), Friedman test (non-parametric test of one-way Repeated Measure Anova) was employed. Wilcoxon signed rank post-hoc test was run for significant effects in Friedman Test and we reported effect size as well (r ; $r = Z/\sqrt{n}$). Statistical Package for Social Sciences (SPSS) was used for analyses.

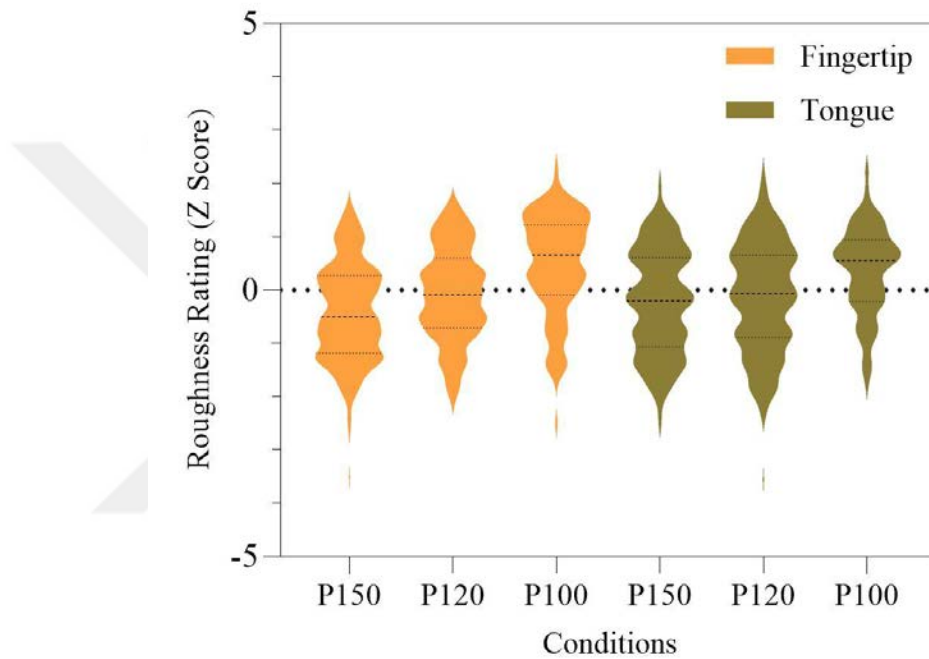
3.5. Results

According to Friedman test results, there were not statistically significant differences for roughness perception when considering tongue and fingertip ($p = .482$, $\chi^2 = .494$ $df = 1$). Besides this, surface discrimination was analyzed for both fingertip and tongue session

separately. Friedman test revealed that participants could discriminate surface with their fingertip ($p = .000$, $\chi^2 = 110.016$, $df = 2$) and with their tongue ($p = .000$, $\chi^2 = 58.683$, $df = 2$). Wilcoxon signed-rank post-hoc test showed that participants were able to discriminate sandpaper with P150 grit number ($Md = -.505$, $n = 270$) from sandpaper with 120 grit number ($Md = -.092$, $n = 270$) and ($Z = -5.087$; $p = .000$, $r = 0.30$) from sandpaper with 100 grit number ($Md = .659$, $n = 270$) ($Z = -9.396$; $p = .000$, $r = 0.57$). In addition to this, they could discriminate sandpaper with 120 grit number ($Md = -.092$, $n = 270$) from sandpaper with 100 grit number ($Md = .659$, $n = 270$) ($Z = -6.652$; $p = .000$, $r = 0.40$) with their fingertip. However, Wilcoxon signed-rank posthoc test revealed that they were not able to distinguish sandpaper with P150 grit number ($Md = -.203$, $n = 270$) from the sandpaper with P120 grit number with their tongue ($Md = -.065$, $n = 270$) ($Z = -1.162$; $p = .245$, $r = 0.07$) whereas they could discriminate sandpaper with P150 grit number ($Md = -.203$, $n = 270$) from sandpaper with P100 grit number ($Md = .552$, $n = 270$) ($Z = -6.953$; $p = .000$, $r = 0.42$) They also could discriminate sandpaper with P120 grit number ($Md = -.065$, $n = 270$) from sandpaper with 100 grit number ($Md = .552$, $n = 270$) ($Z = -6.224$; $p = .000$, $r = 0.37$) (see Figure 9).

Figure 9

Roughness ratings of participants given in fingertip and tongue sessions for sandpapers with P150, P120, P100 grit number.



Moreover, Friedman test revealed harmonicity affected perceived roughness significantly ($p = .014$, $\chi^2 = 5.988$, $df = 1$). Wilcoxon signed rank test indicated that participants perceived surface rougher while they listening to inharmonic sound ($Md = .246$, $n = 90$) than harmonic sound condition ($Md = -.130$, $n = 90$) for sandpaper with P120 grit number by their fingertip ($Z = -2.239$; $p = .025$, $r = 0.23$) whereas there is no statistically significant difference for other sandpapers for fingertip or tongue (see Table 4 for median values of all condition) (see Figure 10 for harmonicity effects on fingertip and Figure 11 for harmonicity effects on tongue).

Table 4

Median values of harmonic and inharmonic sound conditions for Experiment 2.

Harmonicity	Modality	Surface	Median	N
Harmonic	Tongue	P150	-0.68	90
		P120	.322	90
		P100	.584	90
	Fingertip	P150	-.519	90
		P120	-.130	90
		P100	.605	90
Inharmonic	Tongue	P150	.000	90
		P120	-.011	90
		P100	.608	90
	Fingertip	P150	-.130	90
		P120	.246	90
		P100	.883	90

Figure 10

Roughness ratings of participants for sandpapers with P150, P120, P100 grit number in harmonic and inharmonic sound conditions for fingertip session.

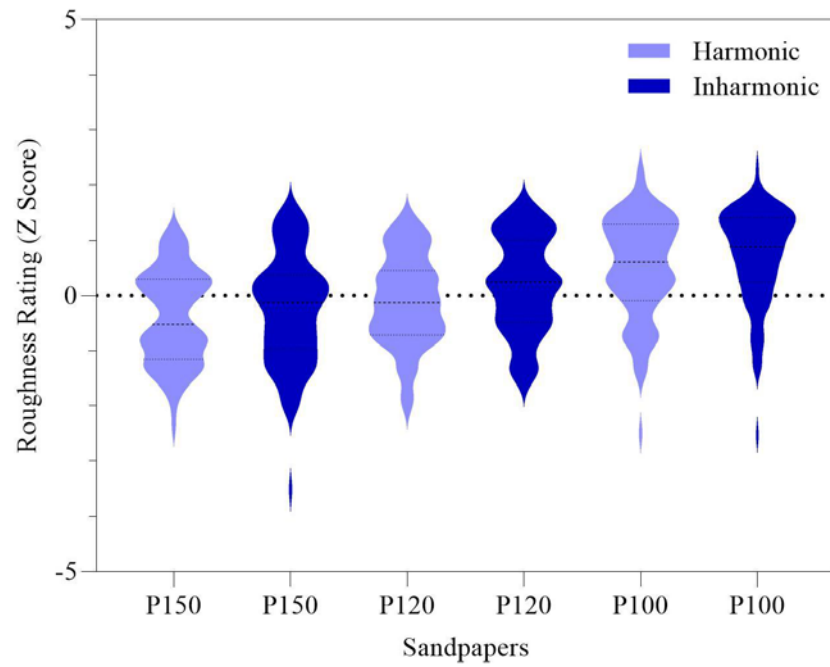
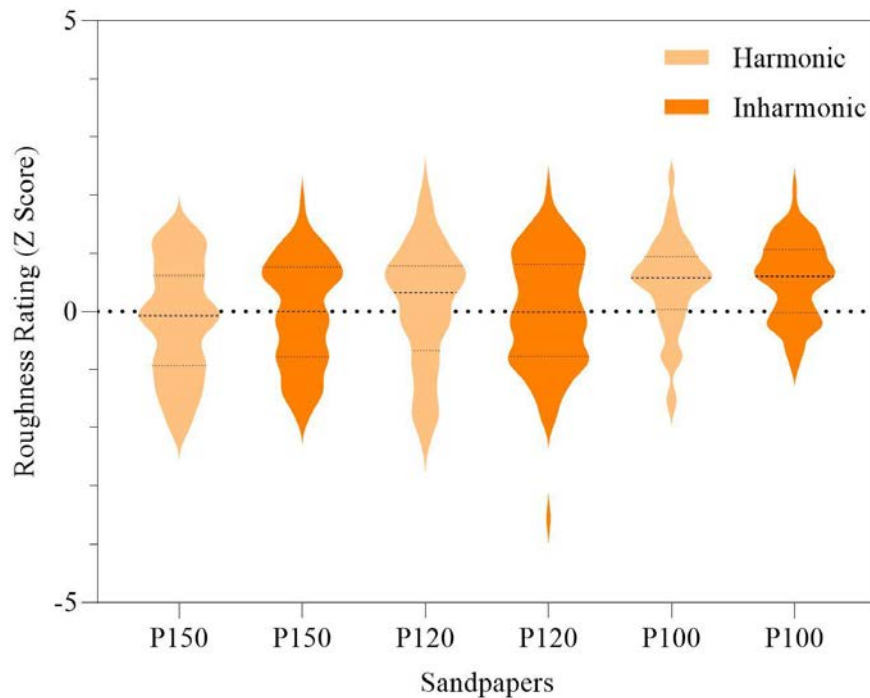


Figure 11

Roughness ratings of participants for sandpapers with P150, P120, P100 grit number in harmonic and inharmonic sound conditions for tongue session.

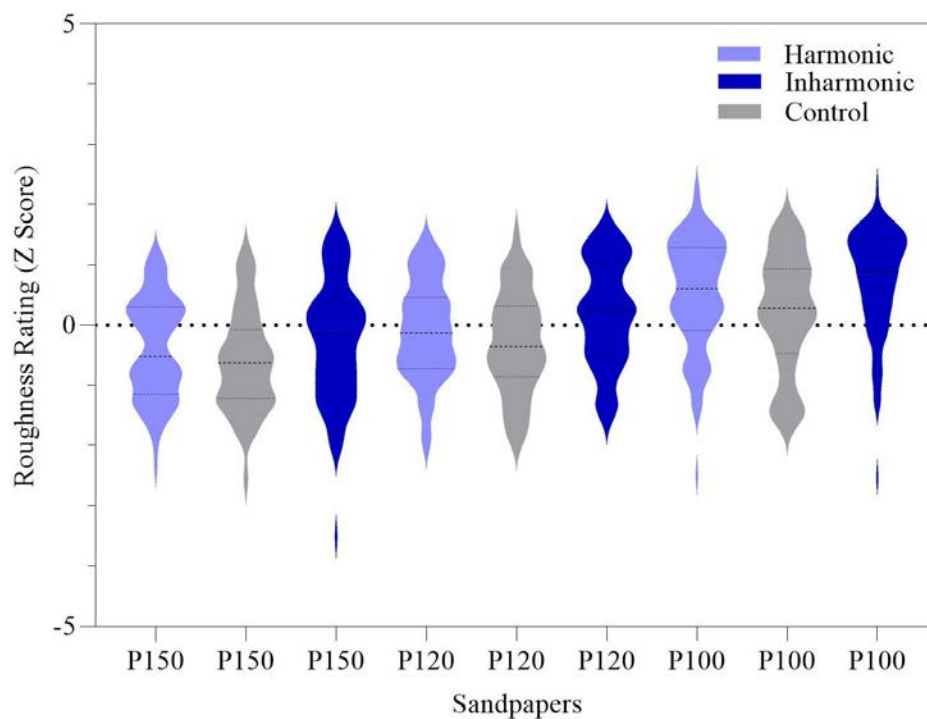


Friedman test showed that there are statistically significant differences between controls and harmonic and inharmonic sound conditions for perceived roughness by fingertip ($p = .000$, $\chi^2 = 155.153$, $df = 8$). Wilcoxon post-hoc analysis revealed that harmonic sound and control condition did not show statistically significant difference for perceived roughness of sandpaper with P150 grit number ($Z = -1.559$; $p = .119$) and sandpaper with P120 grit number ($Z = -1.696$; $p = .090$) for fingertip. However, harmonic sound led to perceive surface rougher in harmonic sound condition ($Md = .605$, $n = 90$) than control condition ($Md = .282$, $n = 90$) for sandpaper with P100 grit number for fingertip ($Z = -2.386$; $p = .017$, $r = .25$). In addition to these results, Wilcoxon post-hoc analysis also showed that participants perceive surfaces rougher in inharmonic sound condition for sandpaper with P150 grit number ($Md = -.130$, $n = 90$) sandpaper with 120 grit number ($Md = .246$, $n = 90$) and sandpaper with 100 grit number ($Md = .883$, $n = 90$)

than control condition (Md=-.631, n=90), (Md=-.357, n=90), (Md=.282, n=90) respectively by their fingertip (see Figure 12).

Figure 12

Roughness ratings of participants for sandpapers with P150, P120, P100 grit number in harmonic, inharmonic sound and control (no sound) conditions for fingertip session.



For tongue, Friedman test results showed that there are statistically significant differences between harmonic, inharmonic sound conditions and control conditions for tongue ($p = .000$ $\chi^2 = 96.366$, $df = 8$). Wilcoxon paired sample t test showed that participants perceived the surface rougher in harmonic sound condition for sandpaper with P150 grit number (Md=-.068, n=90), sandpaper with P120 grit number (Md=.322, n=90) and for P100 grit number (Md=.584, n=90) than control condition (Md=-.641, n=90), (Md=-.615, n=90), (Md=.127,

n=90) respectively for tongue. Moreover, similarly, inharmonic sounds cause perceiving surface rougher for sandpaper with P150 grit number ($Md=.000$, $n=90$), for sandpaper with 120 grit number ($Md=-.011$, $n=90$) and for sandpaper with P100 grit number ($Md=.608$, $n=90$) than control condition ($Md=-.641$, $n=90$), ($Md=-.615$, $n=90$), ($Md=.127$, $n=90$) respectively for tongue (see Figure 13).

Figure 13

Roughness ratings of participants for sandpapers with P150, P120, P100 grit number in harmonic, inharmonic sound and control (no sound) conditions for tongue session.

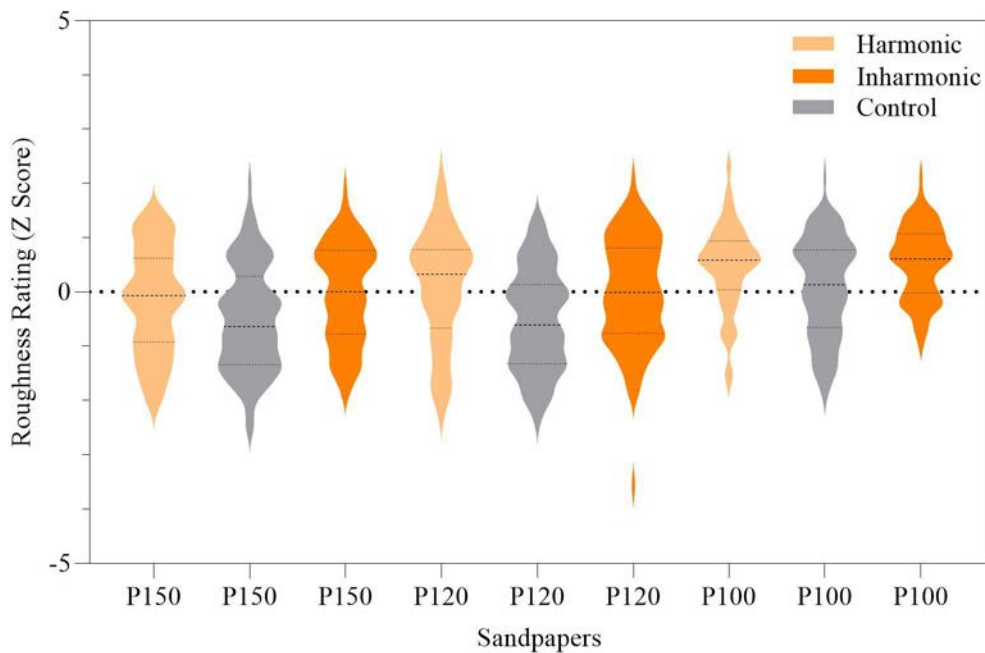


Table 5

Median values of control condition for tongue/fingertip conditions in Experiment 2.

Condition	Modality	Surface	Median	N
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No Sound	Fingertip	P150	-.631	90
		P120	-.357	90
		P100	.282	90
	Tongue	P150	-.641	90
		P120	-.615	90
		P100	.127	90

When analyzing no sound conditions only, participants were not able to discriminate sandpaper with 150 grit number from sandpaper with 120 grit number ($Z = -.176$; $p = .860$) whereas they were able to discriminate sandpaper with 150 grit number from sandpaper with 100 grit number ($Z = -4.050$; $p = .000$, $r = .42$) and sandpaper with 120 grit number from sandpaper with 100 grit number ($Z = -4.303$; $p = .000$, $r = .45$) by their tongue. For fingertip, they could distinguish sandpaper with 150 grit number from sandpaper with 120 grit number ($Z = -2.550$; $p = .011$, $r = .26$), sandpaper with 150 grit number from sandpaper with 100 grit number ($Z = -5.245$; $p = .000$, $r = .55$) and sandpaper with 120 grit number from sandpaper with 100 grit number ($Z = -3.807$; $p = .000$, $r = .40$) (see Table 5).

3.6. Discussion

In Experiment 2, we investigated the effects of harmonic and inharmonic sounds on tactile roughness perception by tongue and fingertip. There is also a control condition in which participants receive no sound when they explore the surfaces and rate perceived roughness. Results of this study showed that harmonicity has no effect on tactile roughness perception for tongue as opposed to our expectation whereas presence of sound causes increase in the perceived roughness for tongue. Inharmonic sound results in rougher sensation for sandpaper with medium roughness level when it is compared to harmonic sound condition for fingertip, same as Experiment 1 results.

Participants were not able to discriminate smooth and medium sandpapers by using their tongue. In contrast with findings of Miles et al. (2018) which indicates tongue has lower Just Noticeable Difference (JND) for roughness perception when it compared to fingertip, our results revealed that participants were not able to discriminate medium and smooth sandpaper from each other. However, they are able to discriminate these sandpapers by using their fingertips. The difference between results of this study and Miles et al's study (2018) may have resulted by the different roughness level of stimuli which were presented to tongue. In their study, they use fine surfaces which were ranging from 0.177 to 0.465 μm , whereas we use surfaces which were ranging from 100 to 162 μm (Federation of European Producers of Abrasives Conversion Charts were used to convert grit numbers to microns) in this current study. Engelen et al. (2005) revealed that, participants perceived roughness with their tongue show increase up to about 80 μm and then settle around 80 μm or decrease. Tongue sensitivity may show better performance for finer surfaces when considering present and previous studies. Object roughness that we interact by using our fingertip and food roughness that we experience during eating in our daily life may cause this sensitivity difference. The reason of why harmonicity effect was not observed in tongue may be due to difficulties on discriminating performance. Fine surfaces may be used than the surfaces in this present study for further investigation of the harmonicity effect on roughness perception of tongue.

Comparing harmonic and inharmonic sound conditions with control condition revealed presence of sound leads to perceive surfaces rougher with tongue regardless of its harmonicity. These results highlighted that increases in the perceived roughness are not related to roughness information obtained from auditory cues for tongue. Zampini and Spence (2004) showed that auditory cues can be more salient than the oral-somatosensory cues since it can capture

participants' attention more than the food's texture. The difference between sound and no sound conditions for tongue may be related to attentional capture effects of the auditory stimuli in this experiment.

In addition to this, harmonicity effect was observed only in medium sandpaper with fingertip as in Experiment 1. Roughness information obtained from auditory stimuli affects tactile roughness perception for this specific roughness level. In the Experiment 1, why this effect was observed only for medium level sandpaper was explained by perceptual ambiguity of the middle one compared to roughest and smoothest one. Thus, the duration of every trial in this experiment was decreased to increase the noise and ambiguity for tactile stimuli. However, increase of ambiguity by decreasing stimuli exposure duration did not cause the tactile roughness discrimination to be more difficult as we can also see from the successful discrimination performance in both control and sound conditions with fingertip. For further research, using surfaces with more than three roughness levels may answer the question whether harmonicity effects are observed when the tactile stimuli are more ambiguous than others.

In Experiment 1, we explained why cross-modal correspondence may occur between auditory and tactile modality for roughness perception. One reason for cross-modal relationships in terms of roughness may be perceptual similarities which result in building cross-modal relationships between sensory modalities (Spence & Deroy, 2013). Suzuki et al. (2008) claimed that white noise impaired roughness estimation function whereas pure tones did not have any effect on it. The reason for this difference between pure tones and white noise may be the acoustical similarity of white noise with rubbing fingertips on a rough surface (Suzuki et al., 2008). Inharmonic sounds also may play a similar role with white noise in this

case since inharmonic tones consist of frequencies with lack of periodicity (Schneider & Frieler, 2008) and perceived to be rough as white noise (Carroll, 1970; Daniel & Weber, 1997).

Besides this, participants also perceive surface rougher in inharmonic sound condition when it is compared to control conditions for all sandpapers in fingertip condition. This is an important finding which shows that auditory roughness effects on tactile roughness perception was not observed only between harmonic and inharmonic sound conditions but also no sound and inharmonic sound condition. This result also indicated that harmonic sounds may not cause perceiving surface smoother since it has no difference with control condition for smooth and medium sandpapers in fingertip. In contrast, inharmonic sounds may result in rougher sensation. This may contribute to the idea that cross-modal correspondence for audio-tactile roughness perception may occur due to metaphorical mapping in terms of 'roughness' between auditory and tactile sensory modalities (Gunther & O'Modhain, 2003) since roughness is both tactile sensation (Heller, 1989) and basic psychoacoustical sensation (Daniel & Weber, 1997). However, participants also perceived rough sandpaper rougher in harmonic sound condition than control condition. Presence of sound may cause increased roughness sensation for rougher surfaces.

These findings not only provide an insight for cross-modal correspondence between sensory modalities but also contribute to the marketing or consumer behavior studies or practical applications in these areas. Multisensory packaging has become an important and rapidly growing area in recent years (Spence, 2016). Packaging and haptic experience is an inseparable part which has an impact on the way we feel about a product (Cheskin, 1957). For instance, Labbe et al. (2013) investigated consumer experience with the package including the sound which generated by touch or feeling elicited by touching to the package for the

naturalness of a dehydrated soup. They found out that tactile cues and especially roughness play an important role on naturalness perception of the product (Labbe et al., 2013). In addition to that Piqueras-Fiszman and Spence (2012) indicated that food texture perception is affected by not only texture of the food itself but also indirect contact with the product's package at the same time.

4. CONCLUSION

Both of the experiments reveal the same result which indicates higher roughness sensation of participants in simultaneous inharmonic sound condition than simultaneous harmonic sound condition for the medium-level sandpaper by their fingertip. In Experiment 1, participants were presented with sounds and the surfaces for 6 seconds whereas they were presented with the stimuli for only 3 seconds in Experiment 2. Same results of both experiments clearly showed that there is a audio-tactile cross-modal relationship for roughness perception. In addition to that, getting the same result in spite of shorter stimuli presentation in the second experiment corroborates the idea that low-level brain mechanisms play an important role on audio-tactile roughness perception (Liew et al., 2017). However, further neuroimaging and electrophysiological studies are required to investigate responsible brain areas and processing stages of audio-tactile cross-modal correspondences.

Besides this, participants only perceived medium-level sandpaper rougher in Experiment 1 and 2 and there was no statistically significant difference for smoothest and roughest sandpapers. They relied on tactile roughness information for smoothest and roughest sandpaper since they are different enough. However, when ambiguity occurred for medium-level sandpaper, our results showed that they also relied on auditory stimuli to make a decision about the surface roughness. Future studies may investigate harmonic and inharmonic sound effects'

on tactile roughness perception by using more than 3 surfaces. Therefore, ambiguity will occur for all surfaces between smoothest and roughest sandpapers. If the reason for observing this effect only for medium level sandpaper is ambiguity, we can expect to see the same effect for all sandpapers between smoothest and roughest ones.

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5. APPENDIX A: RAW DATA

EXPERIMENT 1:

Subject Numbers	Conditions																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	9	9	8	9	4	9	9	7	9	9	9	8	7	9	7	8	9	6	9	8	9	5	9	8	5	7	5
2	7	8	5	6	3	4	5	3	6	4	2	4	3	5	6	7	3	2	7	6	6	3	7	7	5	6	5
3	3	4	5	4	3	6	4	4	6	6	3	4	3	7	5	6	7	4	5	5	7	2	7	6	2	4	2
4	6	8	8	8	5	8	8	6	9	7	5	9	6	9	9	9	9	5	8	9	9	6	8	9	5	9	5
5	9	9	9	9	9	9	9	6	9	6	4	9	6	9	9	9	5	4	9	6	9	7	9	8	8	9	5
6	6	7	6	4	7	8	9	5	7	4	2	6	5	8	9	8	8	5	7	7	8	6	8	7	5	8	7
7	5	6	6	6	5	6	6	5	6	7	5	6	4	6	7	8	8	5	7	8	7	7	8	9	6	8	7
8	2	3	5	6	2	4	7	2	3	4	2	3	2	3	5	4	7	3	4	5	6	3	4	6	3	6	3
9	4	4	5	5	3	6	5	4	7	7	5	6	7	8	9	8	7	5	6	9	6	7	8	7	6	6	3
10	5	5	5	6	4	7	7	5	7	8	8	7	7	8	8	8	8	6	7	8	7	7	9	8	6	7	5
11	8	9	8	8	7	9	4	4	6	5	5	5	4	5	7	6	5	6	7	8	7	4	7	6	6	9	6
12	8	8	9	9	8	9	4	8	9	6	8	8	8	8	8	9	9	9	9	9	8	8	9	8	8	9	9
13	6	6	7	6	6	6	4	5	5	7	4	6	6	6	6	6	6	6	6	5	5	4	4	6	5	5	5
14	8	9	9	9	7	8	4	5	9	8	6	7	7	6	8	9	7	4	9	7	5	6	8	7	7	9	7
15	2	3	3	3	2	4	4	2	6	3	1	3	5	6	3	7	6	3	7	6	7	3	7	8	5	7	3
16	7	8	5	7	5	8	4	5	8	5	4	7	5	8	7	8	6	4	5	4	4	3	8	8	5	7	3
17	9	9	8	7	8	9	4	7	9	9	8	8	9	8	9	9	8	7	8	9	8	9	8	9	8	9	9
18	6	7	8	6	5	7	4	4	5	5	4	6	6	7	7	7	7	4	6	6	7	4	8	6	5	8	5
19	7	6	8	5	4	7	4	4	6	6	5	8	8	7	6	7	8	8	5	7	8	6	7	8	5	7	7
20	7	7	6	7	5	8	4	3	7	7	4	7	5	8	5	7	5	5	7	5	8	5	8	5	5	7	7
21	5	6	6	6	3	8	4	3	6	5	2	4	6	8	6	8	7	4	7	7	5	4	6	5	3	5	4
22	6	7	6	7	7	7	6	7	6	6	5	4	3	3	2	4	3	2	2	1	2	3	2	1	2	1	1
23	9	9	8	8	6	3	8	4	5	7	3	4	7	7	8	9	8	3	9	8	8	8	9	7	5	7	5
24	8	9	5	6	7	9	5	4	8	5	4	5	8	4	7	6	5	3	6	9	3	3	4	6	2	7	7
25	9	9	6	9	5	4	3	3	5	4	3	4	2	5	4	7	4	2	7	7	8	6	8	7	5	7	5
26	8	7	8	6	5	7	7	6	8	8	7	6	6	7	8	8	8	7	8	8	8	8	8	9	6	8	7
27	9	9	8	9	7	8	7	5	8	8	5	8	5	9	8	9	7	5	9	8	5	3	6	5	3	6	3
28	8	8	9	8	7	8	8	6	9	9	6	9	6	8	9	9	8	6	8	8	8	6	8	7	6	8	7
29	8	9	9	6	4	7	6	8	9	9	7	9	6	8	7	9	5	7	9	8	9	6	9	8	3	8	7
30	4	4	4	4	3	3	3	3	4	3	3	4	3	4	5	5	5	3	4	4	5	3	5	4	3	4	3
31	8	7	8	6	5	7	7	6	8	8	7	6	6	7	8	8	8	7	8	8	8	8	8	9	6	8	7
32	7	8	8	9	5	8	7	4	8	6	5	6	7	8	9	8	8	6	6	8	5	7	7	6	5	8	6
33	7	8	8	9	8	8	7	8	9	7	8	7	8	8	8	8	7	9	6	8	8	6	8	9	7	6	8
34	3	4	5	5	4	5	5	3	5	4	2	3	2	5	3	6	2	1	6	3	4	2	3	3	2	3	2
35	8	7	8	8	6	9	6	4	8	6	4	7	5	7	8	9	5	4	8	9	7	5	6	7	4	5	4
36	6	7	3	4	2	7	6	3	7	4	3	2	4	7	4	8	6	7	9	7	7	5	4	3	6	5	4
37	5	6	4	8	3	7	3	2	7	3	2	4	3	8	3	9	3	4	8	3	8	2	9	2	2	3	2
38	9	9	8	9	5	9	6	4	8	5	5	5	7	9	8	9	7	5	9	7	9	7	9	8	7	8	6
39	8	9	8	8	7	8	6	7	9	7	7	7	7	8	7	9	7	6	8	6	8	6	8	6	6	7	7
40	8	8	5	9	4	9	8	4	9	5	3	4	7	9	8	9	7	6	9	9	9	3	8	7	5	5	3

Order of Conditions:

1. Smooth – No Sound
2. First Sequential Harmonic – Rough

3. Second Sequential Inharmonic - Medium
4. Second Simultaneous Harmonic - Rough
5. First Sequential Inharmonic - Smooth
6. Second Simultaneous Inharmonic - Rough
7. First Simultaneous Harmonic - Medium
8. Second Sequential Harmonic - Smooth
9. First Simultaneous Inharmonic - Rough
10. First Sequential Harmonic - Medium
11. Second Sequential Inharmonic - Smooth
12. Medium – No Sound
13. Second Simultaneous Inharmonic - Smooth
14. Second Sequential Harmonic - Rough
15. First Simultaneous Inharmonic - Medium
16. First Simultaneous Harmonic - Rough
17. First Sequential Inharmonic - Medium
18. First Simultaneous Harmonic - Smooth
19. Rough – No Sound
20. Second Simultaneous Inharmonic - Medium
21. Second Sequential Inharmonic - Rough
22. Second Simultaneous Harmonic - Smooth
23. First Sequential Inharmonic - Rough
24. Second Sequential Harmonic - Medium
25. First Sequential Harmonic - Smooth

26. Second Simultaneous Harmonic - Medium

27. First Simultaneous Inharmonic – Smooth

EXPERIMENT 2

FINGERTIP:

Conditions Subject Numbers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	8	7	7	7	8	9	6	5	5	4	4	5	5	6	7	6	8	4	3	6	7	8	5	8	7	8	9
2	5	4	6	7	4	5	3	4	3	4	5	5	3	7	5	4	7	4	5	3	4	4	7	4	7	3	5
3	6	8	7	8	9	8	6	7	5	6	7	8	7	9	8	8	9	8	8	8	7	7	8	7	8	8	9
4	3	4	3	3	5	6	4	3	5	4	3	4	5	7	4	5	7	6	4	5	4	5	7	3	5	4	6
5	3	2	4	5	4	6	4	3	6	5	3	4	3	7	3	4	8	6	2	4	2	5	6	4	8	8	9
6	8	9	9	8	7	9	9	5	9	5	8	8	9	5	9	5	9	8	9	8	5	5	9	5	5	8	9
7	7	8	9	9	9	8	6	8	8	7	6	6	7	8	5	6	7	5	5	4	5	5	7	5	7	7	8
8	7	7	7	4	3	5	6	4	4	6	5	4	4	7	6	5	5	7	6	7	6	6	8	7	7	6	5
9	7	8	2	7	6	8	7	6	8	6	7	8	5	6	7	6	7	8	7	7	5	5	7	6	7	7	8
10	5	6	5	7	6	6	7	5	8	7	6	7	5	8	7	6	9	8	8	8	8	8	9	8	9	9	9
11	6	5	8	8	6	6	8	5	8	7	8	6	7	7	8	6	6	8	7	6	7	7	7	7	5	7	6
12	6	8	9	7	6	9	9	6	9	5	8	9	8	5	8	5	7	9	8	7	6	5	8	6	5	9	8
13	4	5	5	6	4	6	6	4	7	5	6	6	5	8	6	7	8	7	6	7	6	6	8	5	7	7	8
14	8	9	9	7	8	7	9	8	9	7	6	7	5	7	6	8	6	7	8	7	8	8	9	7	8	7	8
15	4	4	6	5	5	7	6	4	6	6	4	4	3	3	2	4	3	3	3	3	2	4	4	3	4	4	3
16	9	9	8	8	8	9	7	9	9	9	7	7	7	8	8	6	7	8	8	9	6	7	8	6	9	8	7
17	3	5	2	7	4	6	3	2	8	6	3	4	2	7	3	6	7	4	2	3	4	6	8	4	6	4	7
18	6	6	5	8	8	9	7	4	8	8	6	7	5	7	4	6	7	6	5	7	6	8	9	5	8	8	8
19	6	5	5	7	5	6	7	7	8	5	4	6	6	7	6	5	7	8	7	6	6	4	7	5	6	8	7
20	4	4	4	5	3	5	4	3	5	4	3	4	3	4	3	3	5	5	3	4	3	4	5	3	4	5	6
21	3	4	4	6	4	6	6	4	8	8	5	7	4	8	3	5	6	4	4	6	3	7	8	3	7	3	6
22	8	5	7	8	7	8	6	7	9	7	4	4	5	8	7	6	9	7	7	8	6	7	9	7	8	5	7
23	4	5	3	6	4	6	4	3	5	6	3	3	2	6	2	3	4	2	1	2	1	1	3	2	5	4	6
24	5	7	6	7	5	8	7	4	6	7	7	7	5	6	3	6	8	5	6	8	2	3	7	5	8	5	6
25	3	5	7	4	8	9	6	8	8	8	4	5	8	7	8	3	5	7	5	3	6	8	9	6	8	6	7
26	7	6	9	9	7	9	9	7	9	7	7	6	6	5	7	6	9	9	5	6	5	5	5	5	5	9	7
27	9	8	9	6	9	8	9	7	8	9	7	8	8	8	8	7	9	7	8	9	9	8	8	9	7	8	9
28	7	8	6	8	7	9	7	8	9	8	8	7	8	7	9	7	9	8	7	9	7	7	8	7	8	9	7
29	8	8	8	9	7	9	6	6	8	9	7	7	7	6	7	6	7	9	8	7	7	8	9	9	8	8	8
30	7	7	7	7	8	8	8	7	7	7	8	8	8	6	7	7	8	7	6	6	5	7	8	7	6	7	7

Order of Conditions:

First Harmonic - Smooth

Second Harmonic - Medium

Third Inharmonic - Smooth

First Harmonic - Rough

No Sound - Medium

Third Inharmonic - Rough

Second Inharmonic - Medium

No Sound - Smooth

First Inharmonic - Rough

Nosound- Rough

First Inharmonic - Smooth

Third Harmonic - Medium

Third Harmonic - Smooth

No Sound - Rough

Second Inharmonic - Smooth

No Sound - Medium

Second Harmonic - Rough

Third Inharmonic - Medium

Second Harmonic - Smooth

First Harmonic - Medium

Nosound - Smooth

Nosound - Medium

Second Inharmonic -Rough

No Sound - Smooth

No Sound Rough

First Inharmonic - Medium

Third Harmonic – Rough

TONGUE:

Conditions Subject Numbers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	6	6	6	7	4	7	6	5	8	8	6	7	5	7	7	4	6	7	8	7	5	8	8	5	6	5	7
2	3	6	5	7	3	8	4	7	6	3	2	7	2	7	7	2	7	7	6	2	2	7	7	2	7	2	7
3	8	3	5	4	4	7	6	7	7	6	6	5	6	5	6	6	7	8	6	7	8	4	6	5	6	8	6
4	2	3	2	2	3	3	4	5	4	4	5	5	5	4	5	5	4	4	4	4	5	4	5	4	5	6	7
5	4	6	4	8	6	6	4	5	7	7	4	7	6	7	6	7	9	5	6	6	7	6	7	4	6	5	7
6	6	9	8	8	5	9	9	6	8	5	8	7	8	5	9	5	8	9	8	9	5	5	9	6	5	9	8
7	7	8	7	8	6	6	7	6	6	7	5	6	7	7	7	5	6	5	7	7	5	4	6	6	6	6	6
8	3	4	4	6	4	5	7	8	7	5	7	8	7	8	9	7	8	6	6	6	4	6	7	6	5	5	6
9	7	5	7	7	4	8	3	5	8	4	6	2	3	5	4	4	7	8	5	6	5	3	8	4	5	7	4
10	8	8	7	8	7	8	7	6	8	8	7	8	8	8	8	7	7	7	7	7	8	7	8	7	8	7	7
11	4	3	3	7	6	6	5	6	5	4	7	8	8	7	7	6	6	7	8	9	5	6	8	6	6	3	7
12	7	7	9	8	5	9	7	4	8	5	8	8	9	4	8	5	9	9	7	8	4	5	9	5	4	8	9
13	7	6	8	8	5	8	6	5	7	6	7	7	7	6	8	6	7	7	8	6	6	6	9	7	7	8	7
14	6	6	7	8	7	7	7	7	7	7	8	7	8	8	8	7	8	6	8	8	7	7	7	8	6	7	7
15	5	8	5	8	5	7	7	7	7	5	6	6	8	7	8	5	6	7	8	5	8	5	7	7	7	5	7
16	5	6	3	8	3	5	7	4	8	6	8	7	8	6	1	5	5	1	4	4	1	6	5	1	5	4	6
17	7	7	4	6	4	5	4	5	6	7	4	8	5	6	4	5	6	5	4	6	4	5	7	4	4	5	6
18	7	8	8	8	5	7	7	7	9	8	6	6	5	8	7	7	8	9	6	6	7	6	7	7	8	8	9
19	6	7	6	7	7	8	8	7	5	6	7	4	7	6	7	8	7	8	4	7	3	7	6	4	7	5	7
20	8	8	8	7	7	8	8	8	9	6	7	8	7	8	8	7	8	7	6	6	8	7	8	7	7	8	9
21	6	7	5	7	7	6	8	4	8	8	7	5	4	8	5	4	8	6	7	7	4	3	6	4	8	4	7
22	7	9	7	8	7	8	6	8	8	9	8	5	6	9	6	8	7	6	8	9	8	5	8	5	6	8	6
23	5	4	3	4	5	3	3	2	4	3	2	2	3	5	4	5	4	6	3	4	2	3	5	2	3	5	4
24	6	7	9	8	4	8	7	4	6	5	6	3	4	7	8	7	7	8	7	8	5	7	8	6	6	6	9
25	5	6	8	9	4	7	7	8	9	9	8	9	5	7	6	7	8	5	3	5	6	3	8	6	7	6	7
26	5	4	5	5	6	7	8	5	7	8	5	7	7	9	6	5	7	5	4	6	7	7	8	7	6	5	4
27	8	9	8	9	8	9	8	9	7	9	9	9	7	9	6	9	7	8	8	9	7	9	9	7	8	3	6
28	6	7	8	8	8	7	7	7	8	8	6	7	7	8	8	6	8	8	7	9	8	5	7	5	6	8	8
29	4	3	4	4	5	6	5	7	6	5	6	5	4	6	6	5	5	6	5	6	3	3	5	4	5	4	5
30	7	8	6	7	6	5	6	4	6	5	5	6	4	4	4	7	7	6	4	6	4	5	7	6	5	7	7

Order of Conditions:

First Harmonic - Smooth

Second Harmonic - Medium

Third Inharmonic - Smooth

First Harmonic - Rough

No Sound - Medium

Third Inharmonic - Rough

Second Inharmonic - Medium

No Sound - Smooth

First Inharmonic - Rough

Nosound- Rough

First Inharmonic - Smooth

Third Harmonic - Medium

Third Harmonic - Smooth

No Sound - Rough

Second Inharmonic - Smooth

No Sound - Medium

Second Harmonic - Rough

Third Inharmonic - Medium

Second Harmonic - Smooth

First Harmonic - Medium

Nosound - Smooth

Nosound - Medium

Second Inharmonic -Rough

No Sound - Smooth

No Sound Rough

First Inharmonic - Medium

Third Harmonic – Rough