Part XI

Free Talk Session 6

TEMPORAL ENSEMBLE CODING OF SUB-SECOND AUDITORY BEEPS: AN MEG STUDY

Lu Guo and Ming Bao
Key Laboratory of Noise and Vibration Research, Institute of Acoustics
Chinese Academy of Sciences, Beijing 100190, China
University of Chinese Academy of Sciences, Beijing 100049, China

Lihan Chen
School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing 100871, China
Key Laboratory of Machine Perception, Peking University, Beijing 100871, China

<baoming@mail.ioa.ac.cn, clh20000@gmail.com>

Abstract

The ability to encode the temporal sensory events is fundamental for adaptive behavior. The present study examined the temporal ensemble coding towards a sequence of sound beeps containing multiple sub-second inter-intervals, with psychophysics and Magnetoencephalography (MEG) recording. Immediately after hearing a sound sequence (6 sounds, with mean inter-interval 600 ms), participants produced time interval which was half, equal, or double of the mean auditory inter-interval (600 ms). Participants showed a general over-estimation of the mean interval, and they produced time interval more accurately for the "double" condition. Moreover, analysis of the auditory evoked component revealed that the M100 amplitude, evoked by the final tone of the preceding sequence, increased in the "half" condition, suggesting that it is task-demanding to segment short time intervals.

Human beings have fascinating abilities to perceive averaging sensory properties of objects and construct statistical representations over various dimensions (Ward et al., 2016). Studies have shown that observers were able to report statistical summaries of properties ranging from motion direction (Dakin and Watt, 1997), size (Chong and Treisman, 2003), to facial identity (de Fockert and Wolfenstein, 2009) and emotion (Haberman and Whitney, 2007). However, these studies were limited to statistical properties of visual stimuli. Later, Albrecht, Scholl, and Chun (2012) explored statistical summarizing in audition with an averaging pitch from a sequence of tones, and the results illustrated that the perceptual averaging could span different sensory modalities and occur efficiently over temporal sequences.

The ability to encode the temporal sensory events and estimate motor-sensory time intervals in sub-second range is fundamental for adaptive behavior (Acerbi et al., 2012; Hellström and Rammsayer, 2004). To our best knowledge, however, few studies have focused on the ensemble coding (i.e., "perceptual averaging") of time interval. To explore how this process operates on a sequence of sound beeps, the present article used psychophysics and Magnetoencephalograph (MEG) recordings to investigate the statistical summarizing in auditory interval duration. By forming the ensemble representation of the temporal information within multiple beeps, human observers could overcome the information overload in otherwise complex acoustic scenes, and use the "averaged" temporal information to predict the target events (Albrecht et al., 2012).

Specifically, we utilized an interval production task, in which participants were required to produce half, equal or double of the mean inter-interval among multiple beeps in a sound sequence, with either a regular or irregular rhythm (different temporal contexts). This experimental design allowed us to test whether individuals could perceive and estimate the average duration of the inter-intervals in the auditory sequence, and how the processing magnitude in temporal domain for the "half", "equal", and "double" estimation were implemented. The results indicated a general over-estimation of the mean interval. M100 amplitude evoked by the final tone of the sequence increased in the "half" condition, showing a demanding task to segment time interval in short range.

Method

Participants

Eight undergraduate and graduate students (4 males; M_{age} = 22.38 years; SD = 2.83 years; age range: 18–25 years) completed the experiments after providing written informed consent and received monetary compensation for their participation. All participants were right-handed, with normal or corrected-to-normal vision and normal hearing. None of participants had a history of psychological or neurological disorders.

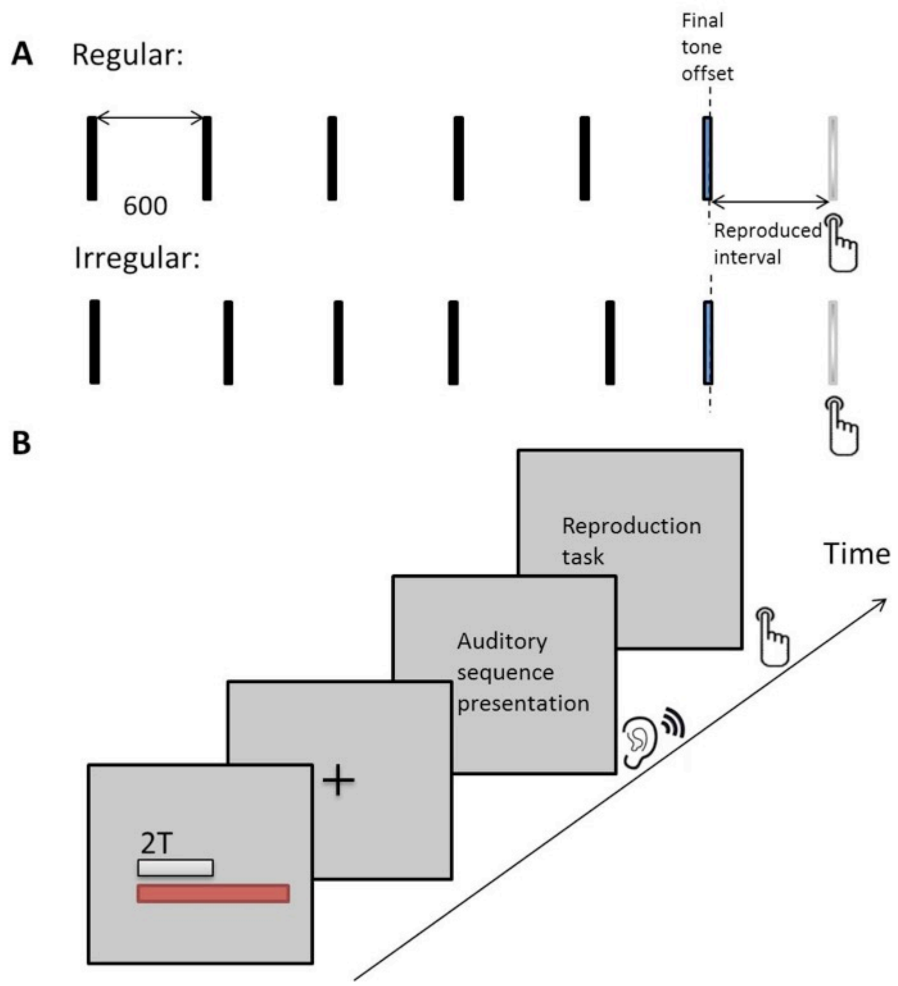

Fig. 1. (A) Schematic representation of the stimuli. The experiment contained two types of stimuli: Regular and irregular sequences. The mean duration of the inter-intervals in both sequence types was set to 600 ms. (B) Time course of a sample trial.

Stimuli and Apparatus

The auditory stimuli were sequences consisting of six 30-ms tones, which were separated by five intervals of either a fixed duration (600 ms) ("regular" sequence) or random intervals between 480 and 720 ms ("irregular" sequence), but the mean interval was 600 ms (Fig. 1A). The frequency of the first five tones was maintained at 1000 Hz, while the last tone changed to 500 Hz, so that it distinguished from the previous five beeps. Moreover, to avoid a repetitive motor response pattern from the participants when reproducing intervals, jitter stimuli consisting of five or seven pure tones were randomly presented in catch trials.

In the experiment, before the sound sequence occurring in each trial, participants were informed of the task conditions with a visual cue. It was composed of two bars, and the ratio of the two in length was set to 2:1, 1:1, or 1:2, to indicate the task of producing the "half", "equal", or "double" of the mean interval of the multiple inter-intervals. Correspondingly, labels of "1/2 T", "1 T", or "2T" were given on the top of the two bars, with "T" referring to the mean interval duration of the subsequent sound sequence.

The computer programs for controlling the experiment were developed with MATLAB (MathWorks Inc.) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The auditory stimuli were generated by a sound card (RME Fireface UFX), delivered binaurally with a tube phone attached to ear plugs inserted into the ear canal, and presented at a comfortable listening level adjusted individually for each participant. Visual stimuli were presented to the participants with a viewing distance of approximately 60 cm, on the center of a LCD screen (100 Hz refresh rate; 1024 × 768 pixel resolution) with a gray background (10.6 cd/m^2 in luminance)

MEG Recording

Neuromagnetic signals were recorded through the Vectorview TM whole-head MEG system (Elekta-Neuromag, Helsinki, Finland) with 306 MEG channels in a magnetically shielded room. MEG data were acquired continuously at a sampling rate of 1000 Hz with participants in seating position.

Design and Procedures

A 2 (auditory sequence: regular, irregular) × 3 (tasks: half, equal, or double) factorial design was implemented in the experiment. There were 5 acquisition runs per participant in the MEG scans. During each run, each experimental condition had 12 trials in succession: 10 trials with the auditory sequence consisting of 6 sound beeps, and the remaining 2 catch trials with jitter stimuli. The presentation order of the experimental conditions within each run was randomized for each participant. Totally, there were 360 trials, 60 repetitions of each of the 6 conditions. Short breaks of 2–3 min were provided after every run.

As shown in Figure 1B, a typical trial in the main experiment started with a visual cue on the monitor lasting for 2800 ms to inform participants of the task conditions. Then a fixation cross appeared at the center of the monitor, with a random duration of 300 - 500 ms. After a blank interval of 100 ms, the auditory stimulus appeared. The sequence began with a standard 30-ms tone (1000 Hz) and ended with a 30-ms target tone (500 Hz). For the regular sequence, the duration of the silent interval was set to 600 ms. For the irregular sequence, it was randomized between 480 and 720 ms. Upon offset of the target tone, participants produced half, equal or double times of the mean auditory inter-intervals in the preceding sequence, by pressing the button “8” with their right index fingers to terminate the estimated duration. Therefore, the duration between offset of the target and the onset of the keypress was the produced subjective interval.

Behavioral Data Analysis

We only focused on the interval reproduction for the auditory sequence consisting of six beeps in the experiment, and trials in which the reproduced interval deviated more than 3 standard deviations from the mean were removed. Then we calculated the mean values of the duration and the Weber fraction (the percentage of duration difference between the reproduced interval and accurate average interval) of the reproduced intervals for each participant and for each experimental condition. For these obtained data, we conducted a repeated measures of ANOVA with temporal rhythms of the sequence (regular, irregular) and tasks (half, equal, and double) as within-participants factors, which were followed by (Bonferroni corrected) post hoc analyses to assess any significant main effects.

Analysis of Event-Related Fields (Sensor Level)

The evoked response analysis was time locked to the onset of the final tone of the sequence. The analysis epochs were 650 ms in total duration, including a 100 ms pre-onset period. The data were baseline corrected to the -100 to -1 ms pre-onset time-window and low-pass filtered at 40Hz. Electrooculographic (EOG) and electrocardiographic (ECG) trace were chosen to be removed from the data.

As we were primarily interested in auditory cortical responses to target sounds (final tones in the sequences), we selected the 78 channels positioned over the estimated location of the auditory cortices in both hemispheres, to examine the 100 msec post-stimulus (M100) responses and further reveal the underlying brain activity in the auditory system. The root mean square (RMS) of the field strength across 78 channels was calculated at each sample point for each condition and participant, and the M100 peak was determined as the peak RMS value in the interval 85–115 ms. For illustration purposes, the group-RMS (RMS of the individual participants' RMSs) time series was plotted (Fig. 3A). However, statistical analysis was always performed on the peak RMS values extracted from each participant's data.

Results and Discussion

Extraction of Statistical Summary in Time Dimension

For the mean durations (Fig. 2A), the main effect of tasks was significant, $F(2,14) = 164.861, p < 0.001, \eta_p^2 = 0.959$. Bonferroni corrected comparison revealed significant differences of the mean durations between “half” (522.2 ms), “equal” (804.3 ms), “double” (1363.3 ms) conditions, all $ps < 0.001$. The main effect of rhythms of the sequence was marginally significant, $F(1,7) = 4.423, p = 0.074, \eta_p^2 = 0.387$, with the mean duration for regular sequences (875.3 ms) shorter than that for irregular sequences (917.9 ms). The interaction effect between rhythms and tasks was not significant, $F(2,14) = 0.261, p =$

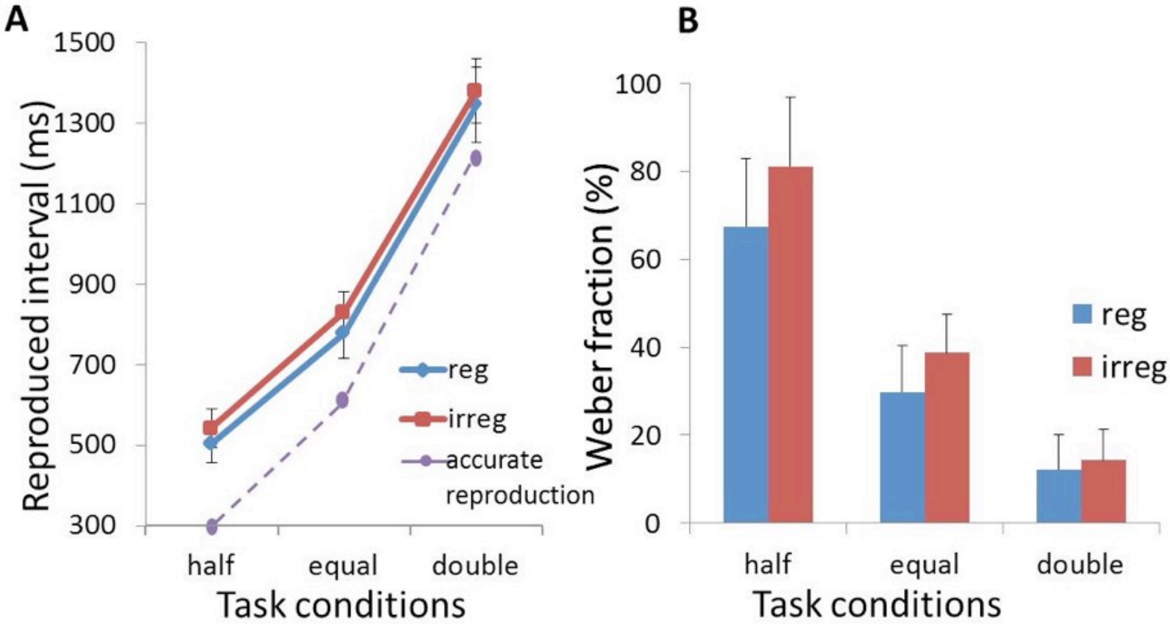

Fig. 2. Group means of the duration and the Weber fraction of the reproduced intervals in different conditions. All the error bars show the associated standard errors of the means.

$0.774, \eta_p^2 = 0.036$. In general, participants performed well in different averaging tasks, resulting in the clearly distinguishable estimated durations from "half", "equal", and "double" conditions. Importantly, this result showed a general over-estimation of the mean interval of the sequence.

For the Weber fractions (Fig. 2B), ANOVA results revealed a significant main effect of rhythms of sequences, $F(1,7) = 6.149, p < 0.05, \eta_p^2 = 0.468$, and also a significant main effect of tasks, $F(2,14) = 22.135, p < 0.001, \eta_p^2 = 0.760$. No significant interaction effect between rhythms and tasks was found, $F(2,14) = 2.976, p = 0.085, \eta_p^2 = 0.298$. Bonferroni corrected comparison showed that the Weber fraction for irregular sequences (44.7%) was significant larger than that for regular sequences (36.5%), $ps < 0.05$. Pairwise comparison also revealed significant differences in the Weber fractions between "half" (74.3%), "equal" (34.3%), "double" (13.3%) conditions, all $ps < 0.05$. The results indicated that participants performed poorly on the inter-interval averaging task for the irregular sequence, which could be attributed to the non-isochronous auditory rhythm. Compared with the "equal" and "double" conditions, the significantly larger Weber fraction in "half" condition may suggest a demanding task to segment time interval in finer scale.

Temporal Encoding: Featured in the M100 amplitudes

ANOVA of M100 peaks evoked by the final tone of the sequence showed that the main effect of tasks was significant, $F(2,14) = 3.92, p < 0.05, \eta_p^2 = 0.359$. However, no significant main effect of the rhythm was found, $F(1,7) = 0.038, p = 0.851, \eta_p^2 = 0.005$, neither the interaction between the two factors, $F(2,14) = 1.058, p = 0.373, \eta_p^2 = 0.131$. Bonferroni corrected comparison revealed that the M100 peak amplitude in "half" condition (225.8 fT) was statistically higher than that in "double" condition (212.2 fT), $ps < 0.05$. The amplitude in "equal" condition (221.1 fT) was statistically equated with those in "half"

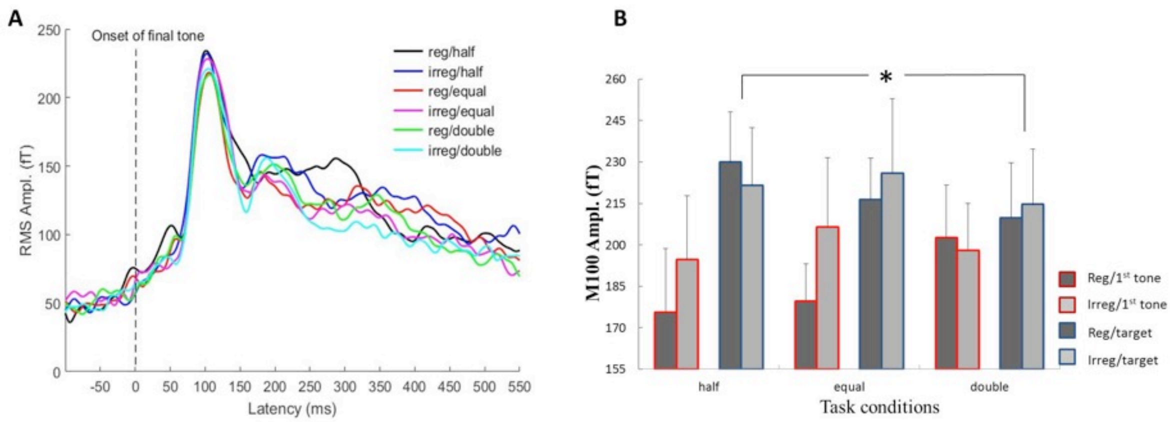

Fig. 3. Results for M100 analysis. (A) Measured M100 responses (group RMS), time locked to the onset of the final tone. (B) The mean peak values of the M100 responses to the first tone and the final tone in the sequence for each experimental condition. The error bars represent standard errors (*$p < 0.05$).

and "double" conditions, all $ps > 0.05$. This result suggested that M100 amplitude was modulated as a function of different task conditions. The M100 measures for the "half" task yielded an enhanced ERF in auditory cortex than for the "double" task.

In addition, to compare the brain responses evoked by auditory beeps in different serial position, we also calculated the peak RMS values of M100 elicited by the first tone of the sequence. These values as well as the evoked responses to the final tone were entered into an analysis of variance (ANOVA), with temporal rhythms ("regular" and "irregular"), tasks ("half", "equal", and "double"), and stimuli ("the first tone" and "target") as within-participants factors. As illustrated in Figure 3B, the results revealed a significant interaction effect between the stimuli and task conditions, $F(2, 14) = 5.198, p < 0.05, \eta_p^2 = 0.426$. No other positive results were found. Further, simple main effects showed that different task conditions only affected the amplitudes of M100 evoked by the target, with a larger peak value in "half" condition (225.8 fT) and a relatively smaller peak value in "double" condition (212.2 fT), $F(2, 14) = 3.92, p < 0.05$. There was no statistical difference in the M100 amplitudes elicited by the first tone between "half" (185.2 fT), "equal" (193.1 fT), and "double" (200.4 fT) conditions.

Based on observations of the amplitude variation of the M100 component evoked by the first and last tone of the sequence, it seemed that M100 components elicited by the first tones varied little in amplitudes across different task conditions, in spite of the fact that the task cue was showed to participants before the sequence presentation. With the following tones unfolding over time, the M100 neural generator was modulated by the task divergence and the modulation contributed to the statistical difference in magnetic response around the temporal points of targets.

In conclusion, we used the auditory sequences to investigate the statistical summary of inter-intervals in the present study. Behavioral results indicated that perceptual averaging task could be implemented in time dimension and occur over temporal sequences, even a general over-estimation was reported when extracting the mean inter-interval duration of the auditory sequence in different tasks. Moreover, analysis of the auditory evoked component revealed a relatively larger M100 amplitude evoked by the final tone of the sequence in "half" condition, showing a demanding task to segment time interval in short range.

References

Ward, E. J., Bear, A., & Scholl. B. J. (2016). Can you perceive ensembles without perceiving individuals?: The role of statistical perception in determining whether awareness overflows access. *Cognition,* 152, 78–86.

Dakin, S. C., & Watt, R. J. (1997). The computation of orientation statistics from visual texture. *Vision Research,* 37, 3181–3192.

Chong, S. C., & Treisman, A. (2003). Representation of statistical properties. *Vision Research,* 43, 393–404.

de Fockert, J., & Wolfenstein, C. (2009). Rapid extraction of mean identity from sets of faces. *The Quarterly Journal of Experimental Psychology,* 62, 1716–1722.

Haberman, J., & Whitney, D. (2007). Rapid extraction of mean emotion and gender from sets of faces. *Current Biology,* 17, 751–753.

Albrecht, A. R., Scholl, B. J., & Chun, M. M. (2012). Perceptual averaging by eye and ear: Computing summary statistics from multimodal stimuli. *Attention, Perception, & Psychophysics,* 74, 810–815.

Acerbi, L., Wolpert, D. M., & Vijayakumar, S. (2012). Internal representations of temporal statistics and feedback calibrate motor-sensory interval timing. *PLOS Computational Biology* 8, e1002771.

Hellström, A., & Rammsayer, T. H. (2004). Effects of time-order, interstimulus interval, and feedback in duration discrimination of noise bursts in the 50- and 1000-ms ranges. *Acta Psychologica,* 116, 1-20.

Brainard, D. H. (1997).The psychophysics toolbox. *Spatial Vision,* 10, 433–436.

Pelli, D. G. (1997). The Video Toolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision,* 10, 437–442.

PHONOLOGY AND PSYCHOPHYSICS: IS SONORITY REAL?

Yoshitaka Nakajima, Kazuo Ueda, and Gerard B. Remijn
Department of Human Science/Research Center for Applied Perceptual Science, Kyushu University, Fukuoka, Japan

Yuko Yamashita
Department of English Communication, College of Engineering, Shibaura Institute of Technology, Tokyo, Japan

Takuya Kishida
Graduate School of Design, Kyushu University, Fukuoka, Japan

Phonology is a field in linguistics, in which speech sounds are classified and related to temporal structures of specific languages. Sound units studied in phonology must be based on subjective properties of acoustic signals. If a way to connect physical and linguistic natures of speech sounds is established, it will form a new basis of a psychophysical investigation. It is known that spectral changes are important for speech communication, but it is not easy to find a paradigm to clarify common mechanisms among different languages.

Ueda and Nakajima (2017, Sci. Rep.) performed factor analyses summing up spectral changes of speech signals between 50 and 6400 (or 7000) Hz. The frequency range was divided into 20 critical-band filters simulating the function of the auditory periphery. The sound intensity fluctuations in these bands were summarized into a fewer number of factors. They discovered that 3-factor analyses led to similar results in 8 languages/dialects in 3 different language families. One of the factors was related to two separate frequency ranges around 300 Hz and around 1500 Hz, and the other two factors to a different frequency range each: around 1100 Hz and above 3300 Hz. It was often possible to separate the first factor into two factors related to one frequency range each, leading to 4-factor analyses.

Nakajima et al. (2017, Sci. Rep.) argued that the factor around 1100 Hz corresponds to what is called 'sonority' in phonology; higher sonority indicates higher suitability for syllable nuclei. They reached this idea examining correspondence between obtained factor scores and phonemes of British English, which were labeled in a speech database. The English phonemes located in the factor space clearly reflected sonority, as it appeared in linguistics literature.

Kishida et al. (2016, Front. Psychol.) improved the above-mentioned factor analysis by shifting the origin to calculate variances, in the variate space, to the acoustically silent point. This enabled them to resynthesize speech directly from factor scores as noise-vocoded speech. If only 1 or 2 factors were extracted, the intelligibility was close to zero, but if 3 factors were extracted, it leaped to $\sim 70\%$. To use more than 4 factors made the intelligibility $> 80\%$.

Yamashita et al. (2013, Front. Psychol.) examined whether the factor corresponding to sonority, hypothetically at that time, would appear in the developmental process of infants. The factor was observed in babbling infants of 15 months of age, and the rhythmic nature of this factor, manifesting a periodicity in a range 0.1–0.4 s, was clearer at higher ages up to 24 months.

The concept of sonority thus seems to combine many different aspects of speech production and perception. (This study was supported by the Japan Society for the Promotion of Science.)

MEASUREMENTS OF THE VELVET HAND ILLUSION

Tetsu Miyaoka
Faculty of Informatics, Shizuoka Institute of Science and Technology
<miyaoka.tetsu@sist.ac.jp>

Abstract

The purpose of the study was to measure the amounts of the Velvet Hand Illusion (VHI)and to propose mechanisms and a mathematical model for the VHI. The experimental stimuli were instruments with two straight rods positioned parallel to each other. The participant held the two rigid rods between his/her hands and moved the both hands simultaneously in an orthogonal direction toward the rods. The participant judged the amounts of the VHI by the magnitude estimation. The results showed the largest amount of VHI when the distance between the rods was 100 mm and showed smaller amounts of VHI when the distances were longer or shorter than 100 mm. We inferred mechanisms which produced the VHI and proposed a mathematical model to explain the VHI amounts.

You can easily feel the Velvet Hand Illusion (VHI) if you hold a coarse-wire net between your hands and move the both hands simultaneously on the net. You feel the surface of each contralateral hand very soft and smooth as if you touch the surface of the velvet. And you do not need even to use the wire for experiencing the VHI. You only need two rods stretched parallel to each other (shown in Fig. 1). If you hold the two rods between your hands and move the hands simultaneously in the orthogonal direction towards the rods, you have the same perception which you had experienced by the coarse-wire net.

The VHI is one of the clearest illusions in the haptics. But few studies were conducted about the VHI (Ohka et al., 2010; Miyaoka, 2012; Miyaoka, 2014; Rajaei et al., 2012; Rajaei et al., 2013; Rajaei et al., 2016). The purpose of the study was to measure amounts of the VHI by the magnitude estimation. We inferred the brain mechanisms which produced the VHI and proposed a mathematical model to explain the amounts of VHI.

Experiment

The purpose of the experiment was to determine amounts of the VHI by the magnitude estimation.

Method

Participants. Eight males and one female in their twenties participated in the experiment. All participants had no experience of psychophysical experiments.

Stimuli. Two straight iron rods covered with plastics were used as stimuli. As shown in Fig. 1, the rods were set in a U-shaped frame. The two rods were stretched parallel to each other. The diameter of the rods was 3 mm. Distances between the two rods (the d in Fig. 1) were seven. They were 20, 40, 60, 80, 100, 120, and 140 mm.

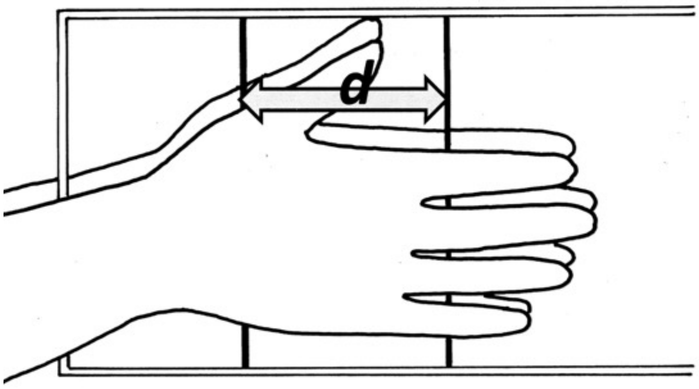

Fig. 1. An example of the stimuli used in the experiment. The participant held two rods between his/her hands and moved the hands simultaneously in the orthogonal direction toward the rods and responded amounts of the VHI. The *d* shows the distance between the rods.

Procedure. The participant sat on a chair and wore an eye-mask to prevent visual inspection of the stimuli. Two stimuli, one was a standard stimulus and the other was a comparison stimulus, were set right and left on the experimental desk in front of the participant. The two stimuli were apart 25 cm to each other. In the magnitude-estimation procedure, a modulus was used. The standard stimulus, the distance between the two rods was 80 mm, was given a modulus "100" for the VHI amount. The participant was asked to give a suitable number to a VHI amount for a comparison stimulus when it was compared with the standard stimulus VHI amount. The experimenter informed the participant which was the standard stimulus before each trial.

The maximum-presenting time for each trial was 15 seconds and the inter-stimulus interval was 20 seconds. Each participant responded 20 times for each stimulus set, therefore the total number of the experimental trials for each participant was 140. Presenting order of each stimulus set was random. Temperature in the laboratory was maintained higher than 25°C in the experiment to avoid the decline of tactile sensitivity.

Results and Discussion

The geometric mean values of the magnitude estimation were calculated based on the experimental data of the nine participants. The results were shown in Fig. 2. The gray diamonds in the figure show the geometric means.

The figure shows that the mean values of magnitude estimation increased when the distances between two rods increased from 20 mm to 80 mm, reached maximum at the 80 mm (the mean-estimation value: 102) and at the 100 mm (the mean-estimation value: 103). The magnitude-estimation values decreased when the distances increased over 100 mm. The magnitude-estimation value was 24.3 when the distance was the 20mm and 66.1 when the distance was the 140 mm.

The participants reported that the tactile impression of the two rods was strong at the 20-mm distance condition. The tactile impression of the 20-mm distance masked the illusion and made the VHI weaker. On the other hand, the participants reported that

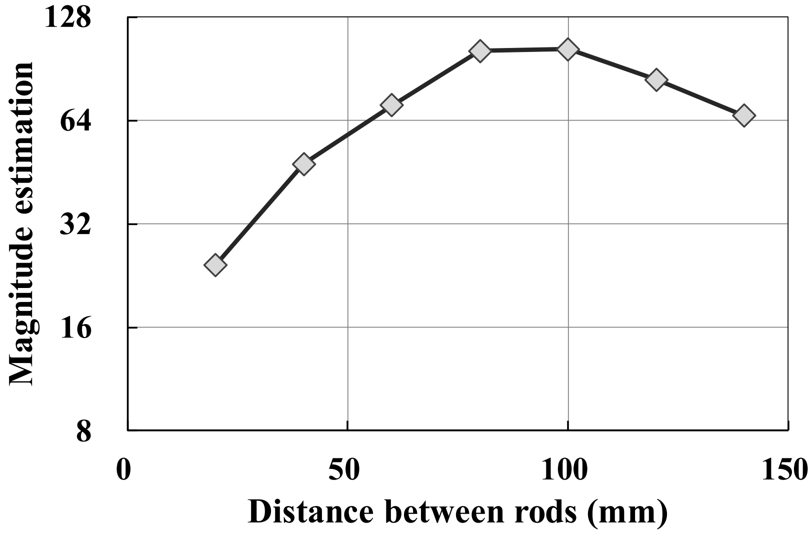

Fig. 2. The amounts of the VHI measured by the magnitude estimation. The vertical axis shows the magnitude-estimation values and the horizontal axis shows the distances between the two rods. Each diamond in the figure shows the geometric mean of the magnitude-estimation values.

the 140-mm distance was too large to hold the two rods simultaneously and to move the hands enough. It made the VHI weaker.

The results of the magnitude-estimation experiment showed that the amounts of VHI were determined by the distances between the rods (the "d" in Fig. 1). The illusion-amount curve was convex upward and the VHI amounts were in the largest level when the distances were between the 80 $\sim$ 100 mm. The VHI amounts decreased when the distances were below 80 mm and over 100 mm. But the reasons that caused the VHI decrease might be different between the short and long d.

We inferred emergence mechanisms of the VHI in the experiment as follows: The participant holds two rods between his/her hands and moves the both hands simultaneously. He/she touches the rods and the surface of the contralateral hand. The rods move on the hands, but the hands do not move to each other because the participant moves the both hands simultaneously. The contralateral-side surface of the hand gives no friction. The participant brain infers that the hands are moving on a surface of something. However, the surface gives no friction. Therefore, the brain concludes that the contralateral-side surface of the hands is very smooth and soft.

General Discussion

Proposal of a Simulation Model

From the experimental data, we induced a simulation model. The model had two hypotheses.

The first hypothesis is as follows: As a distance between the two rods becomes larger and the moving length of hands shortens, the illusion amounts decrease. If a distance between the rods is too large to touch the both rods simultaneously, the participant feels no illusion. The first hypothesis is shown squares and dotted line in Fig. 3 and the

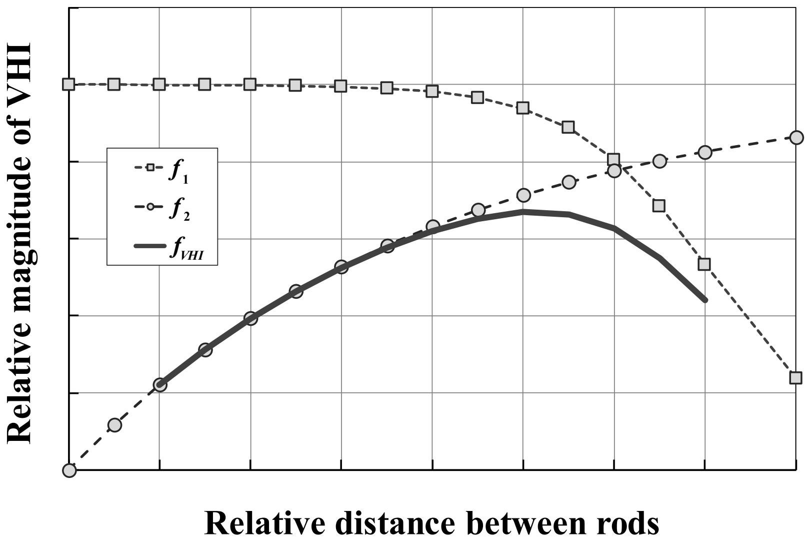

Fig. 3. A simulation model of the VHI. The f_1 in the legend is shown by grey squares and a dotted line. The f_2 is shown by the grey circles and a dashed line. The f_{VHI} is a multiplication of the f_1 and the f_2 and shown by the thick dark-grey line.

equation $f_1(x)$ in the legend is shown as

$$f_1(x) = \frac{\exp\{-a(x-b)\}}{1+\exp\{-a(x-b)\}} \qquad (a > 0,\ b > 0). \tag{1}$$

The second hypothesis is as follows: When a distance between the two rods is shortened, the impression of the rods is stronger and it masks the VHI. This hypothesis

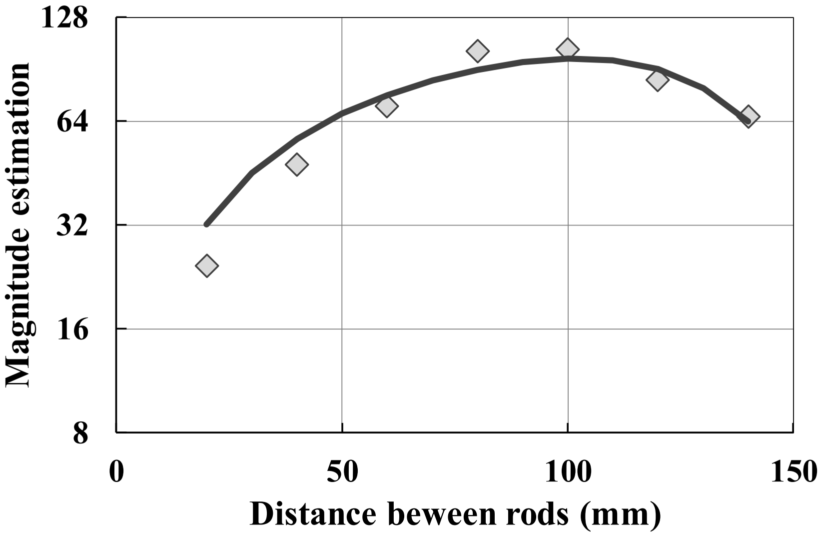

Fig. 4. A curve fitting to the magnitude-estimation data. Each diamond shows the amounts of the VHI measured by the magnitude-estimation experiment. A thick dark-grey line is the fitted curve to the experiment data.

is shown circles and dashed line in Fig. 3 and the f_2 in the legend is

$$f_2(x) = 1 - \exp(-cx) \qquad (c > 0). \tag{2}$$

The total amount of the VHI, the $f_{VHI}(x)$, is shown as a multiplication of the $f_1(x)$ and the $f_2(x)$ and the thick dark-grey line in the figure. The $f_{VHI}(x)$ is

$$f_{VHI}(x) = mf_1(x)f_2(x) = m\frac{\exp\{-a(x-b)\}\{1 - exp(-cx)\}}{1 + \exp\{-a(x-b)\}}, \tag{3}$$

where the m is a parameter determined depending on the unit of measurement. The fitted results of the equation to the magnitude-estimation data are shown in Fig. 4 and the calculated parameters are

$$f_{VHI}(x) = 145\frac{\exp\{-0.0645(x-142)\}\{1 - \exp(-0.0125x)\}}{1 + \exp\{-0.0645(x-142)\}}. \tag{4}$$

The magnitude estimation data are shown as the grey diamonds and the equation $f_{VHI}(x)$ is shown as the thick dark-grey line in Fig. 4.

Conclusion

In this study, we performed the magnitude-estimation experiment and showed the amounts of the VHI were the largest at the distances between two rods were around 100 mm. We inferred mechanisms which produced the VHI. And we proposed a mathematical model to explain amounts of the VHI and fitted the model to the experimental data. We need further studies to reveal neural mechanisms which produce the VHI.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers 25540061.

References

Ohka, M., Kawabe, Y., Abdullah, C., Rajaei, N., Yussof, H. B., and Miyaoka, T. (2010). Investigation on Velvet Hand Illusion using psychophysics and FEM Analysis. *International Journal of Smart Sensing and Intelligent Systems,* 3, 488–503.

Miyaoka, T. (2012). Measurements of Velvet Hand Illusion by the magnitude estimation and paired comparison. *Proceedings of the 28th Annual Meetings of the International Society for Psychophysics,* 268–273.

Miyaoka, T. (2014). A mathematical model to explain the quantity of Velvet Hand Illusion. *Proceedings of the 30th Annual Meetings of the International Society for Psychophysics,* 48.

Rajaei, N., Kawabe, Y., Ohka, M., Miyaoka, T., Chami, A., and Yussof, H. B. (2012). Psychophysical experiments on Velvet Hand Illusion toward presenting virtual feeling of material. *International Journal of Social Robotics,* 4(1), 77–84.

Rajaei, N., Ohka, M., and Miyaoka, T., et al. (2013). Investigation of VHI affected by the density of mechanoreceptive units for virtual sensation. *International Journal of Smart Sensing and Intelligent Systems,* 6(4), 1516–1532.

Rajaei, N., Ohka, M., Nomura, H., Komura, H., Matsushita, S., and Miyaoka, T. (2016). Tactile mouse generating velvet hand illusion on human palm. *International Journal of Advanced Robotic Systems,* September-October, 1–10.