Formulation of tactile Gestalt to express variation in velvet hand illusion caused by out-of-phase cycles of two wires

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Abstract
To develop a tactile display, we focused on the Velvet Hand Illusion (VHI), which is a tactile illusion phenomenon. The most important feature of VHI is that VHI is not generated in one wire but is generated in two or more wires. This means that we recognize the area surrounded by wires as a Gestalt and a smooth surface sensation is generated in the Gestalt. We assume that the VHI mechanism is related to the law of closure and the law of common fate in Gestalt theory. In this paper, we investigate the relationship between VHI and the law of closure by means of variation in a phase difference of two wires’ cyclic movement, and formulate VHI variation, taking into account the law of closure. We try to divide the law of closure into two factors: one of them is a factor of translation and the other is a factor of elasticity. We formulate the tactile Gestalt and verify the validity of this formulation by comparing the result of the psychophysical experiment to the estimation via the formulation. This work shows that the law of closure in the tactile Gestalt consists of the translation factor and the elasticity factor, and the VHI mechanism is described by the formulation of the tactile Gestalt.

Keywords: Actuator system, Virtual reality, Velvet hand illusion, Tactile Gestalt, Formulation

1. Introduction

Recently, Virtual Reality (VR) has been applied to a variety of fields, such as for medical use, entertainment and education (Halvorsen et al., 2006; Matsumura, 2009). Since virtual object handling is the most important issue in VR technology, VR engineers and researchers pay attention to haptic devices capable of presenting virtual tactile and reaction feelings caused by touching a virtual object. Although current haptic devices can provide touch feeling and hardness of the virtual object, it is difficult to provide a smooth feeling. In order to improve the haptic devices, since new actuators are very important, R & D of new actuators is progressing all over the world. However, we try another approach in which tactile illusion is induced using conventional actuator systems. Our study will contribute new uses of actuator systems to VR engineers and researchers.

Fig. 1 Velvet hand illusion generated in the two wires
feel the smooth sensation in our hands when we sandwich the two parallel stretched wires which move back and forth between the hands (Mochiyama et al., 2005) as shown in Fig. 1. So far, we have elucidated factors of VHI intensity control using psychophysical experiments (Ohka et al., 2010; Rajaei et al., 2012; 2016), and human brain network causing VHI using psychophysiology (Rajaei et al., 2018). Especially, in the preceding study (Rajaei et al., 2016), it is shown that two lines caused on a dot-matrix display generate VHI when experimental participants put their hands on the display. This study is a pioneer for usage of VHI on VR devices. Furthermore, in the previous study (Mochiyama et al., 2005), it was found that VHI does not occur for a single-wire movement. This fact is referred in the next chapter as formulating expressions for VHI generation.

Since VHI is generated not in a one-wire movement but a two-parallel-wires movement, we suggest that the investigation of VHI should be conducted from the view point of Gestalt theory (Koffka, 1935). Here, Gestalt is German, and means shape in English. In the human recognition process, a set of information is obtained through sensory organs and is integrated to recognize it; Gestalt shows the set. In visual Gestalt, there are several factors, such as proximity, similarity, closure, and common fate, which are summarized as the principle of Prägnanz in Fig. 2 (Kohler, 1969). Through Gestalt, we can recognize human faces, conversations, and music (Handel, 1989). Since VHI does not occur for the single-wire movement but occurs for the two-wire movement, we consider that two wires constitute tactile Gestalt. In the previous study (Komura & Ohka, 2019), we assumed that VHI is caused by the factor of closure and the factor of common fate to examine minimum stimulus of closure for VHI generation.

In this study, we formulate the tactile Gestalt by using the VHI to find better actuation for VR surface feeling. This is because the formulation is utilized to control VHI intensity and to comprehend the relationship between VHI and tactile Gestalt. In order to address this formulation, we focus on the law of closure and divide the law of closure into two new factors, which are the translation factor and the elasticity factor. We verify the validity of this formulation by comparing the result of the psychophysical experiment to the estimation by this formulation.

2. Formulation of Tactile Gestalt

We consider that VHI is generated through the factors of closure and common fate because VHI is not generated by the single wire movement but the two wires movement (Komura & Ohka, 2019). Furthermore, in this paper, we divide the factor of closure to new sub-factors such as the factor of translation showing movement of the closure region and the factor of elasticity showing expand and contract of the closure region based on the following reasons. That is, although the strongest VHI occurs when the two wires move with in-phase motion, weaker VHI occurs with even out-of-phase motion (Mochiyama et al., 2005).

We assume two wires A and B, which move with simple harmonic oscillation of angular velocity \( \omega \) and amplitude \( r \) (Fig. 1). Since we consider the psychometric phase difference \( \phi' \) between A and B motions, velocities of A and B are
expressed with the following:

\[ v_a = \omega r \sin \omega t \] (1)

\[ v_b = \omega r \sin(\omega t + \phi') \] (2)

We designate \( G_1 \) to VHI generated by the factor of translation. We assume that \( G_1 \) is proportional to the movement distance of two wires in same direction during a cycle. That is,

\[ G_1 = a_1 \int_{0}^{2\pi/\omega} |v_a + v_b| \, dt + b_1 D \] (3)

where \( D \), \( a_1 \) and \( b_1 \) are initial distance between the two wires, and the translation coefficient from distance and the coefficient of \( D \) to VHI intensity. In Eq. (3) the second term is hypothetically added based on the previous result which shows that VHI is proportional to the wire distance \( D \) (Ohka et al., 2010).

If Eqns. (1) and (2) are substituted with Eq. (3), we obtain the following:

\[ G_1 = 4a_1 r(1 + \cos \phi') + b_1 D \] (4)

where this equation holds when \( r \neq 0 \) because VHI does not occur at \( r = 0 \).

Next, we designate \( G_2 \) to VHI generated by the factor of elasticity. We assume that \( G_2 \) is proportional to movement distance of two wires in opposite direction during a cycle. That is,

\[ G_2 = a_2 \int_{0}^{2\pi/\omega} |v_a - v_b| \, dt + b_2 D \] (5)

As same as the factor of translation, Eqns. (1) and (2) are substituted into Eq. (5) to obtain the following equation:

\[ G_2 = 4a_2 r(1 - \cos \phi') + b_2 D \] (6)

where, \( r \neq 0 \).

Finally, we consider the relationship between the psychometric phase difference \( \phi' \) and external phase difference stimulus \( \phi \). As the model of psychometric phenomenon, there are two equations, i.e. Fechner’s equation and Stevens’ equation (Gescheider, 1997a). In this paper, we designate the latter equation to the model:

\[ \phi' = c \phi^d \] (7)

where \( c \) and \( d \) are coefficients determined with psychophysical experiments. For \( G_1 \) and \( G_2 \), we assume that \( c \) and \( d \) are determined to obtain \((c_1, d_1)\) and \((c_2, d_2)\). Consequently, we obtain the following equations for translation and elasticity:

\[ G_1 = 4a_1 r(1 + \cos(c_1 \phi'^{d_1})) + b_1 D \] (8)

\[ G_2 = 4a_2 r(1 - \cos(c_2 \phi'^{d_2})) + b_2 D \] (9)
3. Psychophysical Experiment

3.1 Experimental apparatus

In order to evaluate the formulated equations, we use the experimental results which were performed to evaluate VHI in out-of-phase cycles (Komura et al., 2017). In this experiment, we used two experimental apparatuses. One of them was for VHI induced by phase differences between the two wires motion; we call this apparatus the VHI display. The other was used to provide the standard feeling of surface smoothness using a real velvet textile; we call this apparatus the real velvet display.

First, in the VHI display (Fig. 3), each wire of the two wires is spanned in each polycarbonate frame. Each frame is connected to a turntable through a link. Gear A attached to the turntable engaged with Gear B attached to the handle. If the point of engaging Gears A and B is changed, the phase difference is varied with an interval of 4°. In this experiment, the phase difference is changed with an interval of 20° from 0° to 180°. Since loose wire tension affects VHI intensity, we paid attention to generation of enough tension. In the VHI display, a tester turns the handle to generate out-of-phase wire motion. In the future, since the VHI display will be used in fMRI, we used metal free material for production of this apparatus. Additionally, the rotational radius \( r \), wire distance \( D \), and rotational speed \( \omega \) were constant in this apparatus; these values were 30 mm, 70 mm and 4.33 rad/s, respectively.

Second, the real velvet is used to present standard stimulus. A red-brown velvet textile is installed and spanned in a polycarbonate frame as shown in Fig. 4. The frame is moved through a motor drive table. The mean speed was around 80 mm/s with stroke of 60 mm. As shown in Fig. 4, the participant holds the velvet textile with two hands to feel smoothness. This feeling is used for judgment of VHI intensity as a standard intensity in the flowing.
3.2 Experimental procedure

Ten male Japanese students participated in the psychophysical experiments for our present study and were paid for their participation. Their ages ranged from 22 to 25. All tests were approved by the Ethics Committee of Nagoya University.

Through the VHI display and the real velvet display, we investigated the relationship between VHI intensity and phase difference of two wires. We adopted one standard stimulus of a real velvet textile and 10 kinds of phase difference of 0°, 20°, 40°, 60°, 80°, 100°, 120°, 140°, 160° and 180°.

The presentation procedure was as follows. First, using the real velvet display, the smoothness was presented and the participant memorized the smoothness as a smoothness of 7 (the highest rating). The participants judged VHI intensity generated by the VHI display comparing the VHI intensity with the memorized smoothness. VHI intensity evaluation was expressed with a real number according to magnitude estimation procedure (Gescheider, 1997a) using the modulus which makes the memorized velvet textile feeling become a 7. The presentation order of phase differences was performed at random. Each test was composed of the standard stimulus and 10 phase difference stimuli; six tests were performed for each participant.

The present apparatus does not completely have accurate sinusoidal motion because the experimenter moved the handle of the apparatus. However, since the handle rotating was performed according to auditory instructions generated by a metronome, and the experimenter was sufficiently trained using the metronome to keep a constant rotational speed of the disk before the series of experiments and he used the metronome during actual experiments, we consider that the frame keeps relative accurate sinusoidal velocity variation.

3.3 Experimental result and discussion

Each participant performed the test six times to remove accidental error occurrences in individual measurement. We adopt the mean value of six results as a representative value of the individual. The experimental results are shown in Fig. 5, which shows a relationship between magnitude of VHI intensity and phase difference. In this graph, we can see two types of trends in the range of 0° to 100° and 100° to 180°. As shown in Fig. 5, VHI intensity decreases with increase of phase difference in the range of 0° to 100°. If we obtain a linear regression in the range of 0° to 100°, there is a high correlation factor of 0.97. However, after 100°, we cannot observe significant variation in VHI intensity. If we carefully observe the variation in VHI intensity from 100° to 180°, we can identify a small local maximum at 140°. We conducted an analysis of variance (ANOVA) to compare their magnitudes using the SPSS version 16.0. There was a significant effect of phase difference at the $p < 0.01$ level among the ten conditions [$F(2.413, 21.716) = 5.387, p = 0.009$].

So far, we have believed that major factors for control of VHI intensity are the distance between two wires and the stroke of wire movement. From this experimental result, it is found that the VHI intensity can be controlled through the phase difference in the range from 0° to 100°.

![Fig. 5 Relationship between VHI intensity and phase difference (error bar shows standard error)](image-url)
Since the variation in VHI intensity drastically changes at 100°, as mentioned above, it seemed that the recognition system for the factor of translation is changed to that for factor of elasticity at 100°. That is, although the system related to factor of translation occupies VHI generation before 100°, another system related to factor of elasticity occupies VHI generation after 100°.

4. Evaluation of formulation

Using the formulated equations, we attempt to explain the aforementioned two trends observed in Fig. 5. First, the parameter of tactile Gestalt formulation is calculated by means of fitting the theoretical equations to the experimental result. The result of the fitting is shown in Fig. 6 and the parameter of each factor is described below.

\[ r = 30 \text{ [mm]}, \quad D = 70 \text{ [mm]} \]

\[ a_1 = 0.0108 \text{ [1/mm]}, \quad b_1 = 0.030 \text{ [1/mm]}, \quad c_1 = 1.45, \quad d_1 = 0.4 \]

\[ a_2 = 0.0083 \text{ [1/mm]}, \quad b_2 = 0.023 \text{ [1/mm]}, \quad c_2 = 1.1, \quad d_2 = 1.1 \]

\( G_1 \) corresponds well to the experimental result within 0° to 100°, and \( G_2 \) also corresponds to the slight local maximum that appeared within the 100° to 180° range. This result shows that a factor generating a greater value is selected between the translation factor \( G_1 \) and the elasticity factor \( G_2 \) and that the greater factor is changed at the phase \( \phi = 100° \) from \( G_1 \) to \( G_2 \). Therefore, the intensity of VHI is described as the equation below:

\[ VHI = \max(G_1, G_2) \]

The abovementioned result shows two systems related to \( G_1 \) and \( G_2 \) cause VHI. \( G_1 \) corresponds with the situation of grasping a smooth plate, such as a glass plate, and \( G_2 \) corresponds with the situation of expansion and contraction deformation of a smooth plate, such as a rubber plate.

Finally, we discuss about theoretical/psychological reason expressed by Eq. (13). In psychophysics, if it is well known that there are multiple neural systems for some sensory perceptions. For visual sensation, there are three neural systems such as red, blue and green color perception systems (Gescheider, 1997b); for tactile sensation, the three are four neural systems, which have different relationship between vibrotactile threshold and vibration frequency (Gescheider, 1997c).

Although each neural system has different sensitivity in the respect of physical variables such as time, wavelength
and vibration frequency variation, the threshold curves of each neural system have overlapped portions in the specific region of these physical variables. For example, in the visual sensation, there are three threshold curves of neural systems corresponding to red, blue and green sensations. While the threshold of each system has a local minimum point in the wavelength, each local minimum has different value of abscissa. Since the lowest threshold among three systems at a specific wavelength is observed through psychophysical experiment, the profile generated among a region of wavelength is created with the lowest threshold of overlapped three segments. Then we observe two bending points in the profile caused by switching the neural systems.

If we apply the abovementioned threshold theory in psychophysics to our theory, we assume $G_1$ and $G_2$ as perception systems of tactile Gestalts. In our theory, $G_1$ and $G_2$ switch according to phase difference of wire movements. Since $G_1$ and $G_2$ are magnitude of sensation strength, they are proportional to inverse number of threshold. Therefore, we assumed that we observed the profile produced with higher value of overlapped two systems, which causes a bending point at the phase $\phi = 100^\circ$ as shown in Fig. 5.

This theory can explain difference of $G_1$ and $G_2$ valance, which is possibly caused by different population of human subjects. In Fig. 7, we present two cases of simulation using the present theory: one of them is $G_1$ is stronger than $G_2$; the other is opposite. Since the former case does not show the bending point, we suppose no bending point case is occasionally possible. Thus our theory expresses variety conditions of population.

However, our theory should be checked through another conditions of not only phase difference but also velocity amplitude and the other general vibrotactile statuses. It is noted that the present theory holds under the limited conditions of constant velocity amplitude.

5. Conclusion

In this paper, in order to control VHI intensity and to comprehend the relationship between VHI and tactile Gestalt, we proposed the formulation of tactile Gestalt utilizing the relationship between VHI and the movement of two wires with a phase difference. We assumed that translation factor and the elasticity factor, which are parts of the tactile Gestalt, are important to generate VHI. In order to verify our proposal formulation, we conducted a psychophysical experiment and compared the result to the proposal theory. This work shows that our proposal theory is a very close match to the experimental value. However, it is noted that the present theory holds under the limited conditions of constant velocity amplitude, stroke of wires, and wire distance.

Since the present experiments were performed through relatively young human subjects of 22 to 25 years old, it is noted that the present conclusion is applied to the young generations. We should consider the difference in illusion during age difference as the future problem.

In future work, in order to verify this theory, we should perform another series of psychophysical experiments and verify Eqns. (8) and (9) after parameter estimation. Additionally, since these equations are formulated based on the
assumption of constant $r$, $D$ and $\omega$, the equations should be evaluated with experimental data obtained from variations of $r$, $D$ and $\omega$. Depending on the evaluation result, we will modify the equations to simulate the experimental data because the present equations may not always be perfect. In order to perform the experiments varying $r$, $D$ and $\omega$, we will modify the present apparatus. Furthermore, since it is known that a specific brain area activates when a brain processes information integration such as Gestalt, we will verify whether the brain area activates or not using fMRI or NIRS when VHI occurs.

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