Hand-Motion Perception by Four Haptic Modes: Active/Passive and with/without Fingerpad Cutaneous Sensation*

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Abstract

Two important factors are related to haptic hand-motion perception: one factor is the sensations employed for perception and the other is the person’s initiative in the hand movements. The following two sensations are considered representative for the sensation factor: the proprioceptive sensations that return the physical states of joint rotations and muscle activities with extension and flexion and the cutaneous sensations of fingerpads. Since these are primary and secondary in haptic motion perception, we examined the following two sensation modes: (1) cutaneous-combined proprioceptive mode, “Co” and (2) without-cutaneous proprioceptive mode, “Pr”. The former is expected to surpass the latter. For initiative factors, we considered the following two initiative modes important: (a) active mode, “Ac,” where persons move their hands with their intention and (b) passive mode, “Pa,” where their hands are pulled by a device against their intentions. The former is expected to surpass the latter. Considering these two factors, we examined haptic hand-motion perceptual performances among the following four perceptual modes by psychophysical experiments: (1-a) cutaneous-combined proprioceptive active, “CoAc mode,” (1-b) cutaneous-combined proprioceptive passive, “CoPa mode,” (2-a) proprioceptive active, “PrAc mode,” and (2-b) proprioceptive passive, “PrPa mode”. From the viewpoints of systematic and random errors, statistical test results suggest that two factors, sensation and initiative, almost independently contribute and additively enhance performance: CoAc mode showed the largest sensibility and the minimum random errors. We also found other haptic directional perceptual characteristics in systematic and random errors.

Key words: Cognitive Engineering, Human Engineering, Man-Machine Communication, Muscle and Skeleton, Skin, Haptic Perceptual Errors, Length, Direction, Cutaneous, Proprioceptive, Passive, Active

1. Introduction

Humans can accept such geometrical information of an object as its length and the direction of line segments by pursuing physical contact (1, 2, 3). Therefore, as an alternative for visually impaired persons to create mental images of objects, researchers have been studying human haptic object perceptual characteristics (4, 5, 6). In early stage of studies on
haptic perception, line segments represent the physical objects (7), and such information has previously been provided as raised dots (8, 9) and edges (10), rods, and ditches (11). Lately, due to the development of robotic technologies, objects can be virtually represented by positional feedback and even by force feedback, as in this paper.

Related to haptic contacts, the perceptual process can be categorized from sensation and initiative factors. Representative sensations include cutaneous sensations on fingerpads (where an index fingerpad is most commonly used) and such proprioceptive senses as joint rotation and kinematic/force related to muscle expansions and contractions. For the two sensations, the following two modes can be considered:

(1) cutaneous-combined proprioceptive sensation, “Co,” and
(2) without-cutaneous proprioceptive sensation, “Pr”.

For the initiative factor, two touch schemes can be considered, based on the direction of the initiative between the person and the device.

(a) Persons take initiative against devices and voluntarily move their hands in the perceptual process; this touch scheme is called active, “Ac”.

(b) Vice versa, external haptic devices take initiative against persons where person hands are forcibly moved by the devices; this touch scheme is called passive, “Pa,” (12, 13, 14).

By combining the two factors, we identified that four modes are important in practical situations: CoAc, CoPa, PrAc, and PrPa mode as shown in Table 1.

Table 1 Four modes to be tested

<table>
<thead>
<tr>
<th>Sensation factor</th>
<th>Initiative factor</th>
<th>Active touch</th>
<th>Passive touch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutaneous-combined proprioceptive sensation</td>
<td>CoAc mode</td>
<td>CoPa mode</td>
<td></td>
</tr>
<tr>
<td>Proprioceptive sensation</td>
<td>PrAc mode</td>
<td>PrPa mode</td>
<td></td>
</tr>
</tbody>
</table>

Let’s review existing works on the initiative factor. Hollins et al. (14) proposed a rod length perceptual model under the active touch. With the model, the perceived length contraction effect was quantified: the contraction effect had been originally found by such researchers as Whitsel et al (16). On the other hand, with passive touch, some researchers compared the length perceptual characteristics between Pr and Co sensation with a positional-controlled linear actuator. With Pr and Co sensation taking length and speed as parameters, Terada et al. (13) presented some valuable mathematical models, and reported that the perceived length by CoPa mode was better than PrPa mode although there was no statistical discussion. The Terada model was compared to the models proposed in this paper together with another model by Hollins et al. (14). Contrary to Terada, Wouter et al. (15) found almost no differences between the two sensations. Thus, the effect of the cutaneous sensation has not been clarified, and was examined in this paper. Wydoodt et al. (16) did interesting work on Ac and Pa touches, and investigated how force cues induce bias effects in haptic length perception using a force device called PHANTOM. They introduced four force-disturbed conditions together with an ordinary condition called the force-free condition: in the force-free condition, the line segment lengths were actively explored by subjects without disruptions. For the force-disturbed conditions, they made (a) two types of opposite-force-impressed conditions (elastic and viscous resistant) and (b) two types of forward-force-impressed conditions (partial and full traction). The force-free and the full-traction condition correspond to the active and the passive condition in this work. They reported an interesting length contraction/expansion effect with systematic errors. Length expansion occurred with the opposite-force-impressed conditions, and length contraction occurred with the forward-force-impressed condition, in contrast to the
force-free condition where neither contraction nor expansion occurred. Since only 10 cm of virtual rod length was employed, the length variations of the presented lines were inadequate to quantitatively model the bias effects in their experiments. As a whole, these previous works addressed restricted conditions.

On the other hand, we carried out thorough experiments with four perceptual modes for various lengths and directions, and examined the contribution to the hand-motion perception, i.e., the hand-moved line length and direction perception: how much the cutaneous sensation being added to the proprioceptive sensation enhances perceptual performance, and how much the active touch surpasses the passive one where a force-feedback haptic device (PHANTOM Omni) represented virtual line segments in the active touch. Furthermore, we also examined the length perceptual characteristic from the viewpoint of anisotropic characteristic at specific directions of motions (i.e., the radial tangential effect), and compared the result effect with some existing works by Cheng et al. (2) Day et al. (3) Deregowski et al. (11), Wong et al. (7) and Armstrong et al. (19).

For haptic perceptual characteristic with hand-moving directions, we also obtained another anisotropic systematic error characteristic at specific directions of motions, and compared it with the works by Blumenfeld (20) and Haggard et al.(21). In addition to these, we also presented a random error characteristic with the directional perceptions, and compared it with some existing works by Salada et al., (22) Robert et al. (23), and Najib et al. (24) where only cutaneous sensation on finger pad was employed.

2. Haptic Line-Perceiving Experiments

2.1 Experimental Devices and Conditions

As a force-feedback haptic device, we used PHANTOM Omni (see Fig.1(a)), which is a 3-DOF articulated manipulator that can move its stylus position in the $x$, $y$, and $z$ directions with constant force-based control.

Here, using the function provided by the haptic device, we examined two kinds of man-machine interacting modes that relate to the initiative between persons and the haptic device. (a) One is called active touch, “Ac,” where persons take initiative against a haptic device that provides two virtual walls facing each other 0.5 mm apart and persons can only move their hands in the perceptual process along a straight line wedged between two virtual walls. (b) The other is passive touch, “Pa,” where the haptic device takes initiative against persons and forcibly moves their hands with a predetermined constant 1.2 N in PrPa mode and 1.5 N CoPa mode to approximately equalize the speed in the Pa touch to that in the Ac touch (see Appendix A-1).

The lengths of the presented line segments were 10, 30, 50, 70, and 90 mm, and the directions were $0^\circ$ (rightward direction), $22.5^\circ$, $45^\circ$, $67.5^\circ$, $90^\circ$ (upward direction), $\cdots$, $180^\circ$ (leftward direction), $\cdots$, $270^\circ$ (downward direction), $\cdots$, $337.5^\circ$ at $22.5^\circ$ intervals: the numbers of the lengths and directions were 5 and 16, respectively, and it resulted in a set of 80 (=5×16) lines. The 80 lines were permuted in pseudo-random order, and were divided into 4 subsets of 20 lines. Consequently, 16 subsets per subject were constituted with all the four modes, and the 16 subsets were also permuted in pseudo-random order, subject by subject. Fifteen right-handed male subjects from ages 22 to 35 participated in the experiments. All had normal senses of touch and vision.

2.2 Experimental Procedure

The haptic device presented straight lines with specific lengths and directions on a horizontal plane in the following procedure. Before experiments, after the information having given about an interaction between the haptic interface and subject finger and that between the surface and the subject fingerpad, a preliminary practice of one subset was given for each of the four modes. During experiment, subjects were instructed to close their
eyes, and to focus on the perception of the length and direction of the presented line segment through their Pr/Co sensation. Here we didn’t take any sound-masking procedure since the driving sound generated by the haptic device was small enough not to receive any sound cues for the perception.

1. The subject’s right hand index finger was held by the fingerstall-shaped clamp fixed to the PHANTOM stylus (see Fig.1(c)).
2. The finger was pulled to an origin 15 cm away from the body front in the midsagittal plane (see Fig.1(b) and Fig.3(a)). During one set of line-perceiving experiments, the subject hand was held in one of the following two conditions.
   (a) In the proprioceptive sensation condition, the subjects were instructed to exert their effort to make their hand motion horizontal at the height of 5 cm in the air (see Fig.2(a)). However, the fingertip vertical positions meandered, being away from horizontal straight lines. The meandering made the actual path lengths deviate from the horizontal line length to the value increased by the amount being referred as “length deviation”. The meandering effect will be discussed in 3.1.4.
   (b) For the cutaneous-combined proprioceptive sensation, they put their index fingerpad on a horizontal plane whose surface was made of a lapping film sheet of #2000 (average grain size, 9 μm. Fuji Star Coated Abrasives, Inc.) (see Fig.2(b)). Before exploring the lines, the subjects perceived the quantity of the pressing force of 0.5 N with an electronic force meter and tried to reproduce the force on the horizontal plane in the line-exploring processes.
3. Subject finger was further pulled from the origin to a starting point (see Fig.3(b)).
4. The straight lines were presented in the following two conditions.
   (a) For the passive touch, just after reaching the starting point, subject finger was pulled from the start to an end point (see Fig.3(c)(d)), both of which were pseudo-randomly determined within a 160 mm wide, 140 mm deep workspace.
   (b) In the active touch, just after reaching the starting point, the subjects explored a virtual wall-free pathway being set around the starting point. As soon as they discovered the pathway and identified its direction, they moved their finger at their-own-determined arbitrary speed along it until they felt a dead end. Motion dynamics with four modes were described in Appendix A-2.
5. While their index finger actively/passively moved, the subjects perceived the lengths and directions of the presented line segments using their proprioceptive-alone/cutaneous-combined-proprioceptive sensation.
6. After reaching the end point, their finger was pulled from the end point back to the origin (see Fig.3(e)).
7. After returning to the origin, subjects provided the lengths and the directions they perceived using an answer board that consisted of concentric circles and radial lines (see Fig.1(d)). The crossing points between them were answer candidates. The concentric circles were drawn with radiuses from 5 to 110 mm at 5 mm intervals, and the radial lines were drawn with angles of 0 to 337.5° at intervals of 22.5°. The subjects were not informed of the true values of either the length or the direction with the presented line.

In advance, after having given the information about the task and the knowledge with the four modes from the viewpoints of the interaction between the haptic device and the subject finger and that between the surface and subject fingerpad, we provided subjects a preliminary practice that was composed of four subsets for the four modes under a condition of one subset for each mode.
Fig. 1 Experimental equipment. During experiments, answer board was attached on the rectangular frame, and it was located between the touch plane and the subject eyes.

Fig. 2 Two sensations: Left: proprioceptive sensation; Right: cutaneous-combined proprioceptive sensation

Fig. 3 Line-presenting procedure

(a) Moving from origin to starting point (b) Preparing to move at starting point (c) Halfway
(d) Reaching end point (e) Returning to origin

Fig. 3 Line-presenting procedure
3. Result and Discussion

3.1 Perceptual Lengths

3.1.1 Experimental results

Experimental results for the four perceptual modes, i.e., CoAc, CoPa, PrAc, and PrPa mode, are shown in Fig. 4. Fig. 4(a) shows the means of the perceptual lengths for each of the actual lengths from 10 to 90 mm together with the standard errors shown by error bars. To clarify the differences among the four modes, the systematic errors, i.e., the mean errors of the perceived lengths, and the random errors, i.e., the standard deviation of the perceived lengths, are shown in Fig. 4(b). The lengths were relatively perceived longer in the order of the CoAc, PrAc, CoPa, and PrPa mode. In the next section, we statistically examined the perceptual performance differences among the four modes.

![Fig. 4 Experimental results of perceived line lengths for CoAc, CoPa, PrAc, and PrPa mode](image)

3.1.2 ANCOVA with systematic errors of 4 mode perceptual lengths

(a) Length perceptual model

As for the length perceptual model, referring the general models (14), (19), (13), (24), and considering our experimental result, we employed a power model. That is, the model-calculated length $l_{model}$ of the perceived length $l$ is related to actual length $L$ by

$$l_{model} = \alpha L^\beta, \tag{1}$$

where $\alpha$ and $\beta$ are the proportionality constant and the exponent constant. The constant $\alpha$ represents sensibility, and the other $\beta$ does linearity: the ideal values are 1 for both of the constants.

By taking the logarithm of both the sides, we get a linear model between $\ln l_{model}$ and $\ln L$, which will be compared among the four modes by an analysis of covariance (ANCOVA) as in the followings:

$$\ln l_{model} = \ln \alpha + \beta \ln L. \tag{2}$$

(b) Model fitting with each of the four modes

As the first step of ANCOVA, for each of the joint events by the sensation, the initiative, the direction, and the subject, the unknown parameters $\ln \alpha$ and $\beta$ in Eq. (2) were estimated by a linear least squares method so that the sum of the squared differences between the model-calculated lengths $l_{model}$ and the perceived lengths $l$ would be least: it means that the unknown parameters were estimated to minimize the squared sum of differences of $(l_{model} - l)^2$. That is, we made a pentad of perceived lengths $l_{n}$ [$l_{10}$, $l_{30}$, $l_{50}$, $l_{70}$, $l_{90}$] and the other pentad of actual lengths $L$, [10, 30, 50, 70, 90] for each of the joint events of the four factors: the sensation factor with the levels of Co/Pr, the initiative factor with the levels of
Ac/Pa, the direction factor from 0.0° to 337.5°, and the subject factor. Then, by solving the following observation equation

\[
\begin{bmatrix}
    l_{10} \\
    l_{30} \\
    l_{50} \\
    l_{70} \\
    l_{90}^{\text{CoAc0.0°_Subject1}} \\
    l_{10}^{\text{CoAc0.0°_Subject2}} \\
    l_{30}^{\text{CoAc0.0°_Subject2}} \\
    l_{50}^{\text{CoAc0.0°_Subject2}} \\
    l_{70}^{\text{CoAc0.0°_Subject2}} \\
    l_{90}^{\text{CoAc0.0°_Subject2}} \\
\end{bmatrix}
= \begin{bmatrix}
    1 & \ln 10 \\
    1 & \ln 30 \\
    1 & \ln 50 \\
    1 & \ln 70 \\
    1 & \ln 90 \\
    1 & \ln 10 \\
    1 & \ln 30 \\
    1 & \ln 50 \\
    1 & \ln 70 \\
    1 & \ln 90 \\
\end{bmatrix}
\begin{bmatrix}
    \ln \alpha \\
    \beta 
\end{bmatrix}
\] (3)

the estimates of the unknown parameters were given by

\[
\begin{bmatrix}
    \ln \alpha \\
    \beta 
\end{bmatrix} = \begin{bmatrix}
    1 & \ln 10 & 1 & \ln 10 \\
    1 & \ln 30 & 1 & \ln 30 \\
    1 & \ln 50 & 1 & \ln 50 \\
    1 & \ln 70 & 1 & \ln 70 \\
    1 & \ln 90 & 1 & \ln 90 \\
\end{bmatrix}^{-1}
\begin{bmatrix}
    \ln 10 \\
    \ln 30 \\
    \ln 50 \\
    \ln 70 \\
    \ln 90 \\
\end{bmatrix} .
\] (4)

As a result, the estimated exponents \( \beta \) for all the joint events of the four factors, were seen to be nearly equal to one another around the value of 0.78. Therefore, we applied an analysis of variance (ANOVA) to the \( \beta \) estimates where three factors were examined together with the interaction factor: the sensation factor, the initiative factor and the direction factor (see Table 2). In this work, we applied ANOVA without replication: it means that, as for the error variation, we included not only the variation due to random errors but also that due to individual differences. As shown in Table 2, we concluded that there were no significant differences with the factor effect by either the initiative, the sensation, the direction factor or the interaction. It was very interesting that the exponent \( \beta \) held consistency under the various levels examined in this paper with such the factors as the sensation, the initiative, the direction factor, and the interaction.

The consistency of \( \beta \) permitted us to proceed to the next step of ANCOVA.

Table 2 ANOVA table on the estimated exponents \( \beta \) of CoAc, PrAc, CoPa, PrPa modes and directions

<table>
<thead>
<tr>
<th>Factor to be tested</th>
<th>Variation DOF</th>
<th>Mean square</th>
<th>Test statistics, F-value</th>
<th>Critical value for the significant level of 0.01</th>
<th>Decision of significance of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiative</td>
<td>0.000</td>
<td>1</td>
<td>0.000</td>
<td>6.662</td>
<td>No sig. dif.</td>
</tr>
<tr>
<td>Sensation</td>
<td>0.011</td>
<td>1</td>
<td>0.011</td>
<td>6.662</td>
<td>No sig. dif.</td>
</tr>
<tr>
<td>Direction</td>
<td>1.245</td>
<td>15</td>
<td>0.083</td>
<td>2.058</td>
<td>No sig. dif.</td>
</tr>
<tr>
<td>Interaction</td>
<td>0.039</td>
<td>15</td>
<td>0.003</td>
<td>2.058</td>
<td>No sig. dif.</td>
</tr>
<tr>
<td>Error</td>
<td>43.511</td>
<td>927</td>
<td>0.047</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>44.807</td>
<td>959</td>
<td>0.047</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(c) Model fitting for all four modes

Unknown parameters \( \ln \alpha \) and \( \beta \) in Eq. (2) were re-estimated by the linear least squares method where the \( \beta \) exponent was defined not for each of the joint events by the sensation, the initiative, the direction, and the subject, but for all of them. In this case, the observation equation was given by

\[
\begin{bmatrix}
    l_{10}^{\text{CoAc0.0°_Subject1}} \\
    l_{30}^{\text{CoAc0.0°_Subject1}} \\
    l_{50}^{\text{CoAc0.0°_Subject1}} \\
    l_{70}^{\text{CoAc0.0°_Subject1}} \\
    l_{90}^{\text{CoAc0.0°_Subject1}} \\
    l_{10}^{\text{CoAc0.0°_Subject2}} \\
    l_{30}^{\text{CoAc0.0°_Subject2}} \\
    l_{50}^{\text{CoAc0.0°_Subject2}} \\
    l_{70}^{\text{CoAc0.0°_Subject2}} \\
    l_{90}^{\text{CoAc0.0°_Subject2}} \\
\end{bmatrix}
= \begin{bmatrix}
    10\cdots \\
    10\cdots \\
    10\cdots \\
    10\cdots \\
    10\cdots \\
    10\cdots \\
    10\cdots \\
    10\cdots \\
    10\cdots \\
\end{bmatrix}
\begin{bmatrix}
    \ln 10 \\
    \ln 30 \\
    \ln 50 \\
    \ln 70 \\
    \ln 90 \\
\end{bmatrix}
\begin{bmatrix}
    \ln \alpha_{\text{CoAc0.0°_Subject1}} \\
    \ln \alpha_{\text{CoAc0.0°_Subject2}} \\
\end{bmatrix} \\
\beta
\] .
\] (5)
The test statistic \( t \)-values in Table 3 represent how much the estimates were significantly different from 0. Since the test statistic \( t \)-value of \( \beta \) estimate was much larger than the critical values with a level of significance of 0.001 as shown in Table 3, the \( \beta \) estimate was concluded to be significantly different from 0. It permitted us to proceed to a next step of ANCOVA with respect to \( \ln \alpha \) estimates.

The lines in Fig. 5(b) show the relations between the estimated (i.e., modeled) and the actual lengths; the estimated lengths, so called the model-calculated lengths \( l_{\text{model}} \) were calculated using \( \ln \alpha \) and \( \beta \) estimates. The symbols show the means of the perceived lengths \( l \). Since the lines agreed very well with the symbols, we intuitively see the effectiveness of the fitted models.

For reference, the models with \( \ln \alpha \) and \( \beta \) of Table 3 were compared with the models by Terada et al.(13) and Hollins et al.(14) The model-calculated values for CoAc, PrAc, CoPa, and PrPa mode in this work are shown by the lines, and those by the Terada and Hollins models are shown by symbols (Fig. 5(b)). The Terada model based on the PrPa mode alone, and the other Hollins model did on CoAc one alone, and they did not compare all CoAc, PrAc, CoPa, and PrPa mode. Therefore, the works could not clarify the effect of the sensation and initiative factors on the perceptual performances. Nevertheless, we can say that the four mode models in this work show very good conformity with their works as a whole.

![Graph showing actual and perceived length comparison](image)

**Table 3 Statistical values with \( \beta \) of the power function: \( \beta \) was unified for all four modes**

<table>
<thead>
<tr>
<th>Estimated value</th>
<th>Standard error</th>
<th>Test statistic, ( t )-value</th>
<th>Critical value (significant level= 0.001)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td>0.004</td>
<td>17.5</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Furthermore, we applied an ANOVA to \( \ln \alpha \) estimates, examining three factors as in the above section, and the ANOVA result is shown in Table 4. We concluded that, as with \( \ln \alpha \), there were significant differences with each of the initiative, the sensation, and the direction factor. Based on the result, the effect of the three factors was formulated by Eq.(6). Here, as for the directional factor, we modeled an anisotropic characteristic with \( \ln \alpha \) estimates by a trigonometric regression function, and the unknown parameters were estimated by using a nonlinear least squares method (see Fig. 6). It suggests the followings. The stimuli being explored in five and eleven o’clock direction (=299° and 119°) were judged to be longer than identical amount of stimuli being explored in two and eight o’clock direction (= 29°
and 209°): the former five and eleven o’clock direction are nearly in the arm’s radial direction, and the latter two and eight o’clock direction are nearly parallel to the arm’s tangential direction. The relation is called the horizontal-vertical illusion, and the amount of illusion, i.e., the perceived length ratio of radial to tangential was given by 7% ($=\exp(0.033\times2)$) from Eq.(6). The value of 7% in this work was approximately consistent with those in earlier works: Cheng (2) gave 27% at 130mm length in PrAc mode. Day et al. (3), Deregowski et al. (11), and Wong et al. (7), respectively, gave 4.4 %, 10%, 18% at 75 mm length in CoAc mode, and Armstrong et al. (19) gave some values of about 10% for various lengths of 5, 6, 7, 8, 9cm in CoAc mode. Thus, since the earlier works examined only for the radial and the tangential direction for a specific mode, this work can be credited with a viewpoint of 360°-covering 16 moving directions and of all the four modes.

Together with the directional anisotropy, let’s denote $K_{\text{initiative}}$ as a constant 1 for the Ac touch, -1 for the Pa touch, and $K_{\text{sensation}}$ as another constant 1 for Co sensation, and -1 for Pr sensation. Then, $\ln \alpha$ can be given by

$$\ln \alpha = 0.759 + K_{\text{initiative}} 0.042 + K_{\text{sensation}} 0.024 - 0.033 \sin^2(\theta_{\text{actu}} + 16^\circ) \quad (6)$$

Table 4 ANOVA table on the estimates $\ln \alpha$ for the sensation, the initiative, and the direction factors

<table>
<thead>
<tr>
<th>Factor to be tested</th>
<th>Level</th>
<th>Mean Factor effect</th>
<th>Sample size</th>
<th>Variation DOF</th>
<th>Mean square</th>
<th>Test statistics, F-value</th>
<th>Critical value for the significant level of 0.05</th>
<th>0.01</th>
<th>0.001</th>
<th>Decision of significance of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global mean</td>
<td></td>
<td>0.759</td>
<td>960</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensation</td>
<td>Co</td>
<td>0.783 0.024</td>
<td>480</td>
<td>0.283</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>***</td>
</tr>
<tr>
<td></td>
<td>Pr</td>
<td>0.735 -0.024</td>
<td>480</td>
<td>0.283</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>0.565 1 0.565 16.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.85 6.66 10.9</td>
<td></td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>Initiative</td>
<td>Ac</td>
<td>0.801 0.042</td>
<td>480</td>
<td>0.838</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pa</td>
<td>0.717 -0.042</td>
<td>480</td>
<td>0.838</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>1.675 1 1.68 50.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.85 6.66 10.9</td>
<td></td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>Direction</td>
<td>0.0</td>
<td>0.750 -0.009</td>
<td>60</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22.5</td>
<td>0.729 -0.030</td>
<td>60</td>
<td>0.055</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>45.0</td>
<td>0.752 -0.007</td>
<td>60</td>
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<td>60</td>
<td>0.091</td>
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<td>0.768 0.009</td>
<td>60</td>
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<td>60</td>
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<td>292.5</td>
<td>0.767 0.008</td>
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<td>0.004</td>
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<td>315.0</td>
<td>0.756 -0.003</td>
<td>60</td>
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<td>337.5</td>
<td>0.769 0.010</td>
<td>60</td>
<td>0.006</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>1.360 15 0.091 2.7</td>
<td></td>
<td>1.68 2.06 2.55</td>
<td></td>
<td></td>
<td>1.68 2.06 2.55</td>
<td></td>
<td></td>
<td>***</td>
</tr>
<tr>
<td>Interaction</td>
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<td>0.000 15 0.000 0.000</td>
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<td>1.68 2.06 2.55</td>
<td></td>
<td></td>
<td>1.68 2.06 2.55</td>
<td></td>
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<td>No sig. dif.</td>
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<tr>
<td>Error</td>
<td></td>
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<td></td>
<td>1.68 2.06 2.55</td>
<td></td>
<td></td>
<td>1.68 2.06 2.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td>960 34.59 959 0.036</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

* $P<0.05$, ** $P<0.01$, *** $P<0.001$
### Table 5 Perceptual-length variances for four modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>CoAc</th>
<th>PrAc</th>
<th>CoPa</th>
<th>PrPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance ([\text{mm}^2])</td>
<td>126</td>
<td>142</td>
<td>186</td>
<td>187</td>
</tr>
</tbody>
</table>

#### 3.1.3 Comparisons of random errors among four modes

In this section, we examined random errors of the perceptual lengths. Table 5 shows the random errors, which were represented by the variances of the residuals of the perceived lengths from the estimates obtained from the factor effects in Table 4. As shown in the Table 5, the CoAc mode performed the best from the viewpoint of the random errors, as did the systematic errors. Here, we applied Bartlett’s test, i.e., a multiple-comparison with the variance homogeneity. As a result, it was concluded that there were significant differences among the variances since the chi-square test statistics of 13.8 was greater than the critical value of 11.2 at the 1% significance level.

#### 3.1.4 Meandering effect in the proprioceptive sensation

Fingertip vertical positions meandered from horizontal straight lines in the proprioceptive sense, i.e., in PrAc and PrPa mode, and the meandering resulted in the length deviation from the horizontal line length \(L\). As for PrAc and PrPa mode, let’s denote the means of the deviated lengths as \(L_{\text{PrAc}}\) and \(L_{\text{PrPa}}\), the variances as \(\sigma_{L_{\text{PrAc}}}^2\) and \(\sigma_{L_{\text{PrPa}}}^2\), and the means of the length deviations as \(\Delta L_{\text{PrAc}}\) and \(\Delta L_{\text{PrPa}}\), respectively. The length deviations are shown in Fig. 7, and, specifically, \(\Delta L_{\text{PrAc}}\) and \(\Delta L_{\text{PrPa}}\) were globally obtained as 1.6 mm and as 0.8 mm, and \(\sigma_{L_{\text{PrAc}}}^2\) and \(\sigma_{L_{\text{PrPa}}}^2\) were as 4.0 mm\(^2\) and 0.89 mm\(^2\).

On the other hand, let’s denote the perceptual lengths in CoAc, CoPa, PrAc, and PrPa mode in 3.1.2(c) as \(l_{\text{CoAc}}\), \(l_{\text{CoPa}}\), \(l_{\text{PrAc}}\), and \(l_{\text{PrPa}}\) where \(l_{\text{PrAc}}\) and \(l_{\text{PrPa}}\) were affected by \(\Delta L_{\text{PrAc}}\) and \(\Delta L_{\text{PrPa}}\). Then, the \(\Delta L\)-affected length-contractions having examined in 3.1.2(c) were given by the difference, \(d_{\text{Ac}}= l_{\text{CoAc}} - l_{\text{PrAc}}\) and \(d_{\text{Pa}}= l_{\text{CoPa}} - l_{\text{PrPa}}\). Since \(l_{\text{PrAc}}\) and \(l_{\text{PrPa}}\) were considered to be approximately proportional to the \(L_{\text{PrAc}}\) and \(L_{\text{PrPa}}\), the \(\Delta L\)-removed length \(l_{\text{PrAc}}\) and \(l_{\text{PrPa}}\) were given by \(l_{\text{PrAc}}= l_{\text{PrAc}}/(L+\Delta L_{\text{PrAc}})\approx l_{\text{PrAc}}/(1-\Delta L_{\text{PrAc}}/L)\) and \(l_{\text{PrPa}}= l_{\text{PrPa}}/(1-\Delta L_{\text{PrPa}}/L)\). Then, the \(\Delta L\)-removed length-contraction, \(d_{\text{Ac}}\) and \(d_{\text{Pa}}\) were given by

\[
d_{\text{Ac}} = l_{\text{CoAc}} - l_{\text{PrAc}} \approx (l_{\text{CoAc}} - l_{\text{PrAc}}) + l_{\text{PrAc}} \Delta L_{\text{PrAc}}/L \approx d_{\text{Ac}} \cdot \Delta L_{\text{PrAc}}
\]

\[
d_{\text{Pa}} = l_{\text{CoPa}} - l_{\text{PrPa}} \approx d_{\text{Pa}} \cdot \Delta L_{\text{PrPa}}
\]

These equations confirmed that the length-contractions in Ac touch, \(d_{\text{Ac}}\), was increased from 1.9 to 3.5 (=1.9+1.6) mm, and that in Pa touch \(d_{\text{Pa}}\) was also increased from 3.5 to 4.3 (=3.5+0.8) mm. The increases enhanced the results in 3.1.2(c) that Co sense was superior to Pr sense.

#### Fig. 6 Anisotropic characteristic of the mean of the estimated \(\ln_a\)

- **Mean of \(\ln a\)**
- **Trigonometrical-function-based model**

3.1.3 Comparisons of random errors among four modes

In this section, we examined random errors of the perceptual lengths. Table 5 shows the random errors, which were represented by the variances of the residuals of the perceived lengths from the estimates obtained from the factor effects in Table 4. As shown in the Table 5, the CoAc mode performed the best from the viewpoint of the random errors, as did the systematic errors. Here, we applied Bartlett’s test, i.e., a multiple-comparison with the variance homogeneity. As a result, it was concluded that there were significant differences among the variances since the chi-square test statistics of 13.8 was greater than the critical value of 11.2 at the 1% significance level.

### Table 5 Perceptual-length variances for four modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>CoAc</th>
<th>PrAc</th>
<th>CoPa</th>
<th>PrPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance ([\text{mm}^2])</td>
<td>126</td>
<td>142</td>
<td>186</td>
<td>187</td>
</tr>
</tbody>
</table>
On the other hand, the variances of \( l_{Pr'Ac} \) and \( l_{Pr'Pa} \) in 3.1.3 were affected by \( \Delta L_{Pr'Ac} \) and \( \Delta L_{Pr'Pa} \). If they are denoted as \( \sigma_{l_{Pr'Ac}}^2 \) and \( \sigma_{l_{Pr'Pa}}^2 \), the \( \Delta L \)-removed variances \( \sigma_{l_{PrAc}}^2 \) and \( \sigma_{l_{PrPa}}^2 \) were given by

\[
\begin{align*}
\sigma_{l_{PrAc}}^2 &= \sigma_{l_{Pr'Ac}}^2 - \sigma_{L_{PrAc}}^2 \\
\sigma_{l_{PrPa}}^2 &= \sigma_{l_{Pr'Pa}}^2 - \sigma_{L_{PrPa}}^2
\end{align*}
\]

Specifically, \( \sigma_{l_{PrAc}}^2 = 138 (=142-4.0) \text{ mm}^2 \), and \( \sigma_{l_{PrPa}}^2 = 186 (=187-0.89) \text{ mm}^2 \). Even in this case, the results in 3.1.3 held true that the random errors of 4 modes show no significant difference to one another.

**3.2 Perceptual Directions**

This section describes systematic error characteristics of perceived directions. For all the perceived directions, we calculated the errors from the actual ones. Then, they were examined by statistical F-tests, considering four factors: (1) the initiative factor whose levels are Ac/Pa, (2) the sensation factor whose levels are Co/Pr, (3) the direction factor whose levels are 0°, 22.5°, 45°, 62.5°, 90°, and 337.5°, and (4) the length factor whose levels are 10, 30, 50, 70, and 90 mm.

**3.2.1 Systematic error characteristics**

As for the systematic error, the means of the perceived directional errors for each of the levels were compared to one another using a four-factor ANOVA (Table 6). We found that only the direction factor showed significant difference, and the remaining factors, including the interaction factor, did not.

Therefore, we modeled the directional-factor-related anisotropic characteristic with the mean perceptual directional errors using another trigonometric regression function. By applying a nonlinear least squares method to all the data of the four modes, we obtained the following systematic error model: the perceptual direction \( \theta_{\text{per}} \) [°] is given by actual direction \( \theta_{\text{actu}} \) [°] (see Fig. 7). That is,

\[
\theta_{\text{per}} = \theta_{\text{actu}} - 8.2 - 1.5 \sin (\theta_{\text{actu}} + 60.7),
\]

where the negative values of the angles represent the rotational bias in the clockwise direction. This equation means that the perceived directions suffer from an 8.2°average bias in a clockwise direction.

As with existing work with directional perception, applying a task that arranging thread parallel to the direction of the sagittal plane, Blumenfeld (20) found a characteristic that, the closer to the midsagittal plane the target line was, the larger the bias became from 0 to 14° in the clockwise direction. Haggar et al. (21) also reported similar clockwise-rotation effect: 3.4° in PrAc mode, and 4.9° in PrPa mode. Therefore, we concluded that the bias of 8.2° in this work almost agreed with these results. One reason for the bias is in the posture...
of the forearm direction; the forearm was set in the direction of eleven o’clock (+30°), and the deviation might have caused a clockwise-rotation effect in the directional perception.

The third term in Eq. (7) suggests another interesting characteristic. It means that the subjects tended to perceive in the directions of five, two, eleven, and eight o’clock (= -60.7°, 29.3°, 119.3° and 209.3°) up to 1.5°. Such bias effect was seen in cognitive maps: subjects perceived road shapes to be at angles that were closer to 90° from the direction of forward motion (25, 26).

Table 6 Four-factor ANOVA with systematic errors of four modes

<table>
<thead>
<tr>
<th>Factor to be tested</th>
<th>Sample size</th>
<th>Variation</th>
<th>DOF</th>
<th>Mean variation</th>
<th>Test statistics, F-value</th>
<th>Critical value (Level of significance)</th>
<th>Decision of significance of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiative</td>
<td>4800</td>
<td>488</td>
<td>1</td>
<td>488</td>
<td>2.18</td>
<td>3.84, 6.64, 10.80</td>
<td>Not sign.</td>
</tr>
<tr>
<td>Sensing</td>
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<td>432</td>
<td>1</td>
<td>432</td>
<td>1.93</td>
<td>3.84, 6.64, 10.80</td>
<td>Not sign.</td>
</tr>
<tr>
<td>Direction</td>
<td>4800</td>
<td>29435</td>
<td>15</td>
<td>1962</td>
<td>8.78</td>
<td>1.67, 2.04, 2.52</td>
<td>Not sign.</td>
</tr>
<tr>
<td>Length</td>
<td>4800</td>
<td>170</td>
<td>4</td>
<td>42.4</td>
<td>0.19</td>
<td>2.37, 3.32, 4.62</td>
<td>Not sign.</td>
</tr>
<tr>
<td>Interaction</td>
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<td>9</td>
<td>60</td>
<td>0</td>
<td>0.00</td>
<td>1.32, 1.48, 1.67</td>
<td>Not sign.</td>
</tr>
<tr>
<td>Error</td>
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<td>226</td>
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</table>

From the variances in Table 7, the standard deviation was derived as 15°, and it corresponds to a JND of 11°. The JND value in this work employing the cutaneous and proprioceptive sensations well agreed with those in existing works employing the cutaneous sensation alone: Salada et al. (22) applied the adjustment method and obtained a JND of 7.49°, Robert et al. (23) obtained a JND of 20.0° where the directional setting was fixed in the radial direction, and Najib et al. (24) presented a JND of 14° where 16 moving directions covering 360° were employed.

4. Conclusion

We examined haptic hand-motion perceptual performances among the following four perceptual modes by psychophysical experiments: (1-a) cutaneous-combined proprioceptive active, “CoAc mode,” (1-b) cutaneous-combined proprioceptive passive, “CoPa mode,”
(2-a) proprioceptive active, “PrAc mode,” and (2-b) proprioceptive passive, “PrPa mode”.

We found the following for the moved length perception:

(1) Among the four modes, CoAc mode was more proactive than the others from the viewpoints of both systematic and random errors: the constant $\alpha$ for the CoAc mode was the largest, which means CoAc mode showed the largest sensibility.

(2) We assumed a power model, $l = \alpha L^\beta$, containing the proportional and the exponent constant $\alpha$ and $\beta$ to the perceived lengths, and the regressed models were found to be effective.

(3) The model’s exponent constants $\beta$ were not significantly different than others among the four modes, and was obtained as 0.79.

(4) As for the proportional constant $\ln \alpha$, the sensation, the initiative, and the directional factor almost independently contributed and additively enhanced the perceptual performance. We also quantitatively determined the effects of the cutaneous sensations, the subject initiatives, and the direction by 0.024, 0.042, and a 0.033 amplitude of trigonometric bias, respectively, together with the global mean of 0.759.

As for the moved directional perception, the following results were found.

(1) The subjects perceived the moving directions by another trigonometric systematic error with 1.5° amplitude and 8.2° bias in the clockwise direction.

(2) They perceived the moving directions with random error of 15° by standard deviation.

In the future, we will develop methodologies to enhance the line perceptual performance, e.g., the application of raised dots and lines to provide haptic-based line presenting devices for the visually impaired persons.

Acknowledgements

This work was supported by KAKENHI (Grant-in-Aid for Scientific Research (B), No. 21300307) from Japan Society for the Promotion of Science (JSPS).

References


(26) Naoyuki Oi, Takayoshi Okita, and Hironobu Takahashi, A Study on the Recognition of
Appendix

A-1 Tractional Force in Passive Touch

Tractional forces in the two passive touches were determined by a preliminary experiment employing three subjects as in the following.

Step 1 Subjects having been instructed to naturally touch surfaces, forces by which fingers contacted on surfaces were measured in CoAc mode. The between-subject mean of the contact forces was obtained as 0.5 N. Therefore, in the next step as well as in the main experiment, subjects were instructed to touch the surfaces with the force of 0.5 N in the Co sensation, i.e., CoAc mode and CoPa mode.

Step 2 Finger-moving speeds were measured in the active touch. Then, the between-subject means of them were obtained as 64 mm/s in PrAc mode and as 62 mm/s in CoAc mode (see Appendix A-2).

Step 3 Relationships between haptic-device-exerting tractional forces and finger-moving speeds were calibrated in each of the two passive touch modes, i.e., PrPa mode and CoPa mode (see Fig. A-1). Then, based on Fig. A-1, the tractional forces in the passive touches were determined as 1.2 N in PrPa mode and 1.5 N in CoPa mode.

![Fig. A-1 Finger-moving speeds as functions of tractional forces in CoPa mode and PrPa mode](image)

A-2 Motion Dynamics with Four Modes

The subject hands move depending on individual characteristics in the active mode. On the other hand, the haptic device works with a force control scheme in the passive mode where a stepwise force was applied to drive the hand. Therefore, we must check consistency among the speeds of the four modes because a big difference of magnitude may affect the perceptual performance.

Taking some examples of a 90 mm line CoAc mode with a subject, the variations of the actual speed against the position are shown in Fig. A-2. Suffering large perturbation, the speed suddenly was raised up at the beginning, then, increased gradually, and, finally, suddenly fell down at the goal position. To compare the speeds for all the four modes, the speed data at 8, 28, 48, 68, and 88 mm were extracted for each of the subjects and plotted (see Fig. A-3). Although the magnitudes of the speeds fairly differed from person to person, they basically showed similar patterns. The mean speeds of the CoAc, CoPa, PrAc, and PrPa modes were 64, 77, 62, and 89 mm/s, respectively. The relative differences among the mean speeds were less than 22 %, and were considered small enough to compare the
perceptual performances among the four modes: almost no speed-caused contraction effects were reported over 50 mm/s in the passive touch speed-controlled experiments (20).

Fig. A-2 Examples of speed variations in the CoAc mode: series of raw speed data are plotted against pathway positions

Fig. A-3 Relationships between mean speed and way point position in each of four modes: the lines correspond to subjects, and the symbols on the lines represent mean speeds at way points