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COORDINATION BETWEEN VISION AND HAPTICS REVEALED THROUGH ASYMMETRY OF CROSS-MODALITY MATCHING FOR OBEJCT SIZES

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SUMMARY

In the present study, the coordination between vision and haptics in size perception was examined by magnitude estimation (ME), magnitude production (MP) and cross-modality matching (CMM). The ME and MP data showed that a metric property of vision was characterized as linear, whereas that of haptics was characterized as nonlinear. We found an asymmetry in CMM between sizes perceived visually and by touch. The results indicate that the seen and felt sizes may not be transformed straightforwardly but may be coordinated by subsystems within each modality leading to a motor signal for grasping action and a visual signal for the visual apprehension of the haptic attributes of an occluded object.

Key Words: size perception, vision, haptics, cross-modality matching

1 Introduction

Our everyday interactions with the world involve coordinated visual-haptic perceptions, and the problem of visual-haptic sensory integration has a long history since the philosophical puzzle known as the Molyneux problem was posed, that is, “if a blind man were given sight, would he be able to recognize objects he had previously only touched?”[1]. Recent studies of visual-haptic sensory integration have revealed that when we handle an item while looking at it, haptics and vision play complementary roles and sensory inputs are weighted according to the quality of information they provide. It has been shown that visual information and haptic information are integrated in statistically optimal fashion: visual signals have a higher weighting than haptic signals in forming an impression of size or height if there is limited information presented in the haptic modality, but if visual cues are ambiguous or weak, or degraded by extraneous visual noise, they carry less weight, and haptic cues become dominant[2), 3), 4), 5)]. It has also been shown that visual and haptic percepts are compared with each other to evaluate their reliability and that these reliabilities determine how cues are combined during three-dimensional visual perception[6), 7), 8), 9)]. These studies of sensory integration suggest that vision and haptics share a common spatial frame of reference or coordinate, with similar representations for objects regardless of whether they are perceived through vision or through touch. However, vision and touch explore the world in very different ways and each of these sensory systems has unique properties. How visual and haptic signals are coordinated into a common frame of reference to access their reliability is an open question, to which the present study is addressed.

Vision and haptics differ with respect to both metrics and frames of reference. The visual system uses a retinocentric frame of reference and represents metrics, such as length or size, in retinotopic representations of the visual field[10)]. On the other hand, haptics is a perceptual system mediated by two afferent subsystems, cutaneous and kinesthetic[11), 12)]. With regard to size, Berryman et al.[13)] have shown that haptic-based size perception occurs in two steps: first, cutaneous afferents signal skin contact and detect the object’s surface properties and, second, proprioceptive afferents signal finger spread. The haptic system uses a hand-centered frame of reference and represents metrics on the basis of biomechanics. Moreover, there is a line of evidence that supports dissociation between visual signals for perception and for action within the visual modality, revealed by the relative insensitivity of reaching and grasping to pictorial illusions such as horizontal-vertical illusion[14)], Ebbinghaus illusion[15)] and Ponzo size-contrast illusion[16)]. Although functional dissociations between visually controlled grasping and perceptual estimates of size in pictorial illusions are controversial, it has been pointed out that the nature of the perceptual and grasping tasks is at the core of the issue and that the important distinction could lie in the frame of reference used to perform the task[17)]. It may be appropriate to ask the question whether, in each of vision and haptics, partly interconnected systems use different frames of reference in different tasks.

The present study aims to ask the question of how visual and haptic signals of size are coordinated into a common frame of reference to enable them to be integrated. In order to reveal the nature of the interconnected system subserving visual-haptic perceptions of size and grasping, we carried out three sets of experiments. In the first set of experiments, we carried out psychophysical measurements for visual and haptic size perception employing the magnitude estimation procedure (ME). In the visual ME experiment (ME-V), the size of an object perceived by the eyes depends solely on visual information, while, in the haptic ME experiment (ME-H), the size of an occluded object grasped by a hand depends solely on haptic (proprioceptive) information from joint, muscle spindle and skin afferents signaling the distance between the fingers[13), 18)]. These measurements enabled us to reveal the nature of metric encoding in retinocentric and hand-centered coordinates, respectively. In a second set of experiments, the nature of the metric representation was further investigated by magnitude production procedure (MP, the visual magnitude production (MP-V) and the proprioceptive magnitude production (MP-P)). In a third set of experiments, we investigated coordination between visual and haptic information by employing a cross-modality matching procedure (CMM). In the haptic-to-visual CMM experiment (CMM-HV), subjects determined the size of visual stimuli in order to produce a sensation magnitude proportional to the touch-perceived size of an occluded object. In the visual-to-proprioceptive CMM experiment (CMM-VP), they determined their grasp aperture in order to produce a sensation magnitude proportional to the visually perceived size. The CMM experiment enabled us to test the hypothesis of the existence of functionally dissociated subsystems within a modality. If visual and haptic metrics were transformed into each other in a straightforward manner via perceived magnitude, perceptual estimates would not be dissociated from grasping. On the other hand, if visual and haptic metrics were transformed with each other in a complex manner, perceptual estimates would be dissociated from grasping, that is, vision for size perception and vision for grasping, haptics for size perception and haptics for visual representation. On the basis of the results, a possible mechanism for coordination between vision and haptics was proposed.

2 Methods

Subjects. Twelve undergraduate and graduate students (11 males and 1 female, 21-25 years old) of Kyoto Institute of Technology took part in the experiments. They were all right-handed and had normal or corrected-to-normal visual acuity.

Stimulus and Apparatus. The visual stimulus was a horizontal line or an outlined circle, generated by a personal computer (PC; Dell Inspiron 710m) with MATLAB software, and presented at the center of an LCD monitor (Iiyama ProLite E17025; size: 337 (W) x 271 (H) mm with a resolution of 1,024 (W) x 768 (H) pixels). The length of the line and the diameter of the circle varied from 20 to 100 mm in 10-mm steps. The width of the line was 0.4 mm, and its color was black (luminance =0 cd/m^2) presented on a white background (46 cd/m^2).

The haptic stimulus was a rectilinear wooden block or a cylindrical block, presented in a custom-made box, which occluded the stimuli from the subject's view. The length of the rectilinear block and the diameter of the cylindrical block were variable and the same as the visual stimuli. The height and width of the rectilinear block were 30 and 12 mm, respectively, and the height of the cylindrical block was 30 mm (accuracy of ±1 mm).

Subjects' grasp apertures were measured using a touch panel (Elo Touch Systems ET1537L) and recorded on a PC. The spatial resolution of the touch panel was 0.074 mm (H) x 0.056 mm (V). The LCD monitor and touch panel were located in front of the subject. The stimulus display was viewed from a distance of 60 cm without stabilizing the subject's head. The box for haptic stimulus presentation was located on the right side of the subject. The LCD monitor was surrounded with a black curtain.

Procedure. Before each experiment, subjects performed 5 practice trials. Subjects were asked to judge the length of the line or the rectilinear block, or the horizontal diameter of the circle or the cylindrical block. The order of the 6 experiments described below was counter-balanced across the subjects.

ME-V: In each trial for the line stimulus, a standard stimulus was shown for 1 sec, and, after a 2-sec interval, a test stimulus was shown for 2 sec. Then, the subject was asked to assign a number to the perceived length of the test stimulus compared with the perceived length of the standard stimulus. The subject responded by pressing the appropriate positions of the touch panel (0-9 digits on a cover-sheet placed on the touch panel), and an 'enter' position. The next trial was initiated 2 sec after the subject pressed any position on the touch panel.

ME-H: In each trial for the rectilinear-block stimulus, the subject grasped a standard stimulus for 3 sec with the thumb and forefinger, and, after a 2-sec interval, grasped a test stimulus for 3 sec. The intervals for grasping were controlled by visual cues presented on the LCD monitor. The two stimuli were presented in a box occluding them from the subject's view. Then, the subject was asked to assign a number to the perceived length of the test stimulus compared with the perceived length of the standard stimulus. The other procedures were the same as in the ME-V experiment.

MP-V: In each trial for the line stimulus, a standard stimulus was shown for 1 sec, and, after a 2-sec interval, a stimulus number was presented for 2 sec. Then, the subject was asked to adjust the length of the visual stimulus (i.e., line) to produce a visual magnitude corresponding to the presented number. The subject responded by pressing the appropriate positions of the touch panel indicated on a cover-sheet (which increased or decreased the length of the visual stimulus). The next trial was initiated 2 sec after the subject pressed any position on the touch panel.

MP-P: In each trial for the rectilinear-block stimulus, the subject grasped a standard stimulus for 3 sec with the thumb and forefinger, and, after a 2-sec interval, a stimulus number was presented for 2 sec on the LCD monitor. The standard stimulus was presented in a box occluding it from the subject's view. Then, the subject was asked to adjust the distance between the thumb and forefinger to produce a proprioceptive magnitude corresponding to the presented number and asked to press the touch panel with the 2 fingers, keeping the inter-finger distance constant. The touch panel was occluded with a cover so that it could not be seen by the subject. The inter-finger distance was recorded by PC. The next trial was initiated 1 sec after the subject pressed any position on the touch panel.

In the 2 ME and 2 MP experiments, the length of the standard stimulus was 60 mm and was

assigned a modulus value of 100. The experimental procedures for the circle and cylindrical-block stimuli were the same as those for the line and rectilinear-block stimuli, except that the subjects were asked to judge the length of the horizontal diameter of the stimuli.
CMM-VP: In each trial for the line stimulus, a visual stimulus (i.e., line) was shown for 1 sec, and then, after a 2-sec interval, the subject was asked to match the distance between the thumb and forefinger to the visually perceived length of the line, and asked to press the touch panel with the 2 fingers, keeping the inter-finger distance constant. The touch panel was occluded with a cover so that it could not be seen by the subject. The inter-finger distance was recorded by PC. The next trial was initiated 1 sec after the subject pressed any position on the touch panel.
CMM-HV: In each trial for the rectilinear-block stimulus, the subject grasped a haptic stimulus (i.e., block) for 3 sec, and, after a 1.5-sec interval, was asked to match the length of the visual stimulus (i.e., line) to the haptically perceived length of the block. The subject responded by pressing the appropriate positions of the touch panel indicated on a cover-sheet (which increased or decreased the length of the visual stimulus). The next trial was initiated 1 sec after the subject pressed any position on the touch panel.

The procedures of CMM experiments for the circle and cylindrical-block stimuli were the same as those for the line and rectilinear-block stimuli, except that the subjects were asked to respond on the basis of the perceived length of the horizontal diameter of the stimuli.

In the 12 experiments, 5 trials were carried out for each of the 9 test stimuli (20-100 mm) in a randomized order, resulting in a total of 45 trials for each experiment.

3 Results

Owing to the subjects incorrectly touching the response panel (e.g., double-touch by a single finger), data from 60 trials (0.9% of the total of 6,480 trials) were discarded. Data from the ME experiments, averaged over the 12 subjects, were well described by a simple power function (Fig. 1(a), (b)). The individual difference was very small, as indicated by the error bars in the figure. There was no significant difference between the psychophysical functions for the line or rectilinear-block stimuli (○) or for the circle or cylindrical-block stimuli (●). There was a significant difference between the psychophysical functions for the visual and haptic perceptions of size. The results of the ME-V experiment (Fig. 1(a)) showed a nearly linear function of physical length (i.e., the psychophysical exponent is about 0.9: 0.85 for line and 0.99 for circle stimuli (Table 1)), which is consistent with a previous study[19)]. This indicates that the visual system represents a target on the retinocentric coordinate where the metric property is characterized by a linear function of the physical length. On the other hand, the results of the ME-H experiment (Fig. 1(b)) showed a nonlinear function with an exponent larger than 1.0 (about 1.6: 1.55 for rectilinear-block and 1.67 for cylindrical-block stimuli (Table 1)). This indicates that the haptic system represents a target on the hand-centered coordinate, where the metric property is characterized by the nonlinear (power) function of the physical length (Fig. 1(b)).

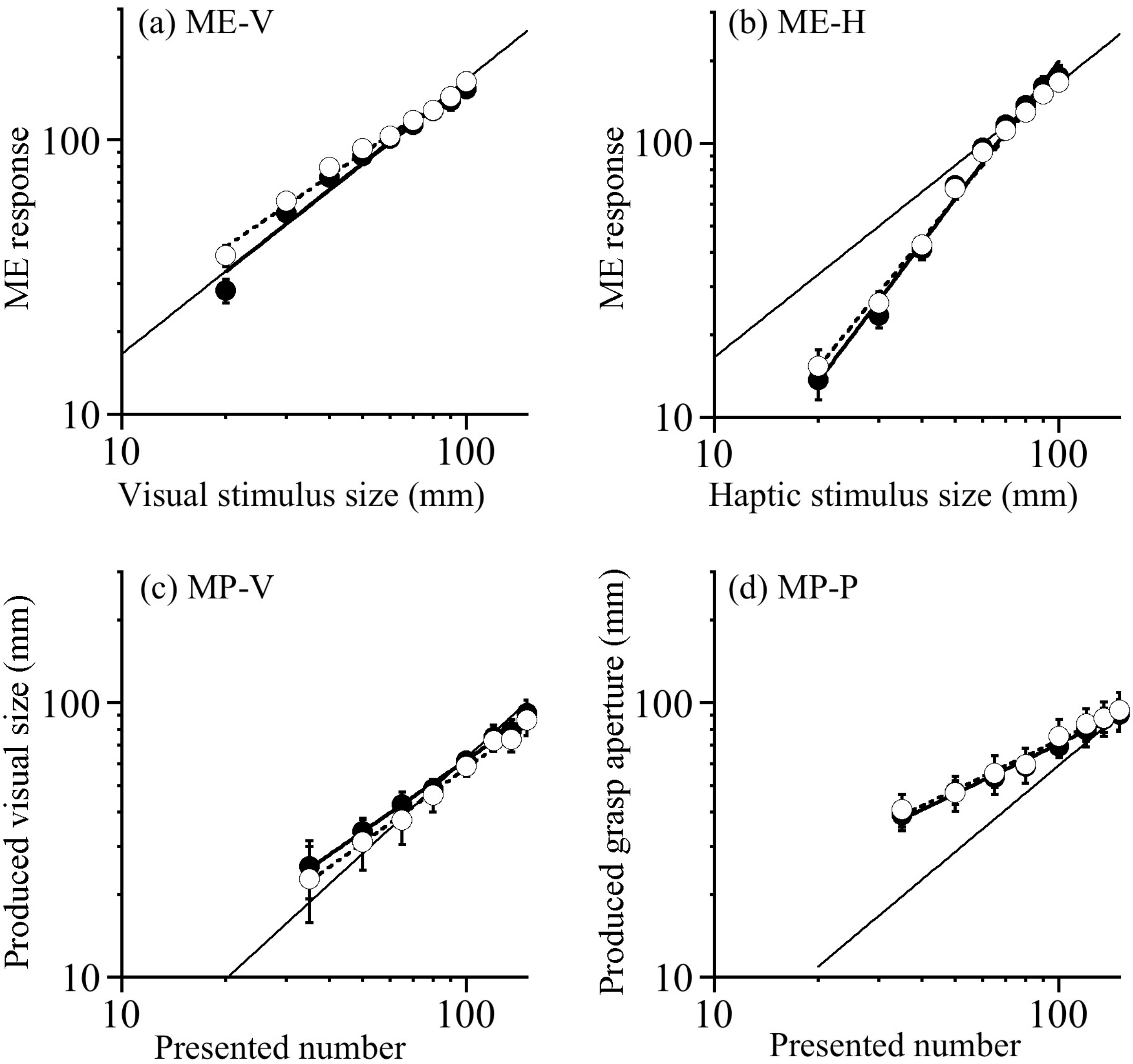

Figure 1: The results of ME ((a), (b)) and MP ((c), (d)) experiments. Data points indicate the average of 12 subjects, and error bars show ± 1 SD. Solid thin lines show functions with a slope of 1.0. (a) Open (○) and filled (●) circles show ME responses for the line and circle stimuli, respectively, as a function of the visual stimulus size. Dotted and solid lines are the best-fitting power functions obtained by the least-squares procedure. (b) Open (○) and filled (●) circles show ME responses for the rectilinear- and cylindrical-block stimuli, respectively, as a function of the haptic stimulus size. Dotted and solid lines are the best-fitting power functions. Solid thin lines in the two panels pass through the point for stimulus size=60 mm and modulus value =100. (c) Open (○) and filled (●) circles show the produced visual size as a function of the presented number for the line and circle stimuli, respectively. Dotted and

solid lines are the best-fitting power functions obtained by the least-squares procedure. (d) Open (○) and filled (●) circles show the produced grasp aperture as a function of the presented number for the rectilinear- and cylindrical-block stimuli, respectively. Dotted and solid lines are the best-fitting power functions. Solid thin lines in the two panels pass through the point for presented number =100 and standard stimulus size =60 mm.

Table 1: Psychophysical exponents and proportionality constants of ME and MP and CMM experiments.

		phychophysical exponents	proportionality constants	correlation coefficient
ME-V	line	0.85	3.15	1.000
	circle	0.99	1.73	0.993
ME-H	rectilinear	1.55	0.15	0.993
	cylindrical	1.67	0.09	0.990
MP-V	line	0.91	0.89	1.000
	circle	0.87	1.13	1.000
MP-P	rectilinear	0.60	4.59	1.000
	cylindrical	0.61	4,38	1.000
CMM-VP	line	0.50	9.85	0.980
	circle	0.49	10.0	1.000
CMM-HV	rectilinear	1.15	0.41	1.000
	cylindrical	1.00	0.54	1.000

The differential property of metric between vision and haptics was further confirmed by the results of the MP experiments, as shown in Fig. 1(c), (d). Data from the MP experiments, averaged over the 12 subjects, were also well described by a simple power function. The individual difference was comparable to that in the ME data. There was also no significant difference between the data for the line or rectilinear-block stimuli (○) or for the circle or cylindrical-block stimuli (●). The results of the MP-V experiment (Fig. 1(c)) showed a nearly linear function of physical length (i.e., the psychophysical exponent is about 0.89: 0.91 for line and 0.87 for circle stimuli (Table 1)). On the other hand, the results of the MP-P experiment (Fig. 1(d)) showed a nonlinear function with an exponent smaller than 1.0 (about 0.6: 0.60 for rectilinear-block and 0.61 for cylindrical-block stimuli (Table 1)). The exponent of 0.6 for the MP-P data was the inverse of the exponent of 1.6 for the ME-H data, confirming the nonlinear transformation of size in haptics/proprioception.

Data from the CMM experiments (Fig. 2) were consistent with a simple power function. Again, there was no significant difference between the line or rectilinear-block stimuli (○) and the circle or cylindrical-block stimuli (●). Individual differences in the CMM experiments were similar to those in the ME and MP experiments (Fig. 1), as indicated by error bars. It should be noted here that the psychophysical functions were significantly different depending on which modality signal was inputted. When subjects varied their grasp aperture in order to produce a sensation magnitude proportional to the visually perceived size (CMM-VP (Fig. 2(a)), the psychophysical exponent was smaller than 1.0 and approximately 0.5 (0.50 for line and 0.49 for circle stimuli (Table 1)). On the other hand, when subjects varied the visual stimulus size in order to produce a sensation magnitude proportional to the touch-perceived size for an occluded stimulus (CMM-HV (Fig. 2(b)), the psychophysical exponent was approximately 1.0 (1.15 for rectilinear-block and 1.00 for cylindrical-block stimuli (Table 1)). The difference between the CMM-VP and CMM-HV functions indicates that the modality of an input signal strongly influences coordination between visual and haptic information.

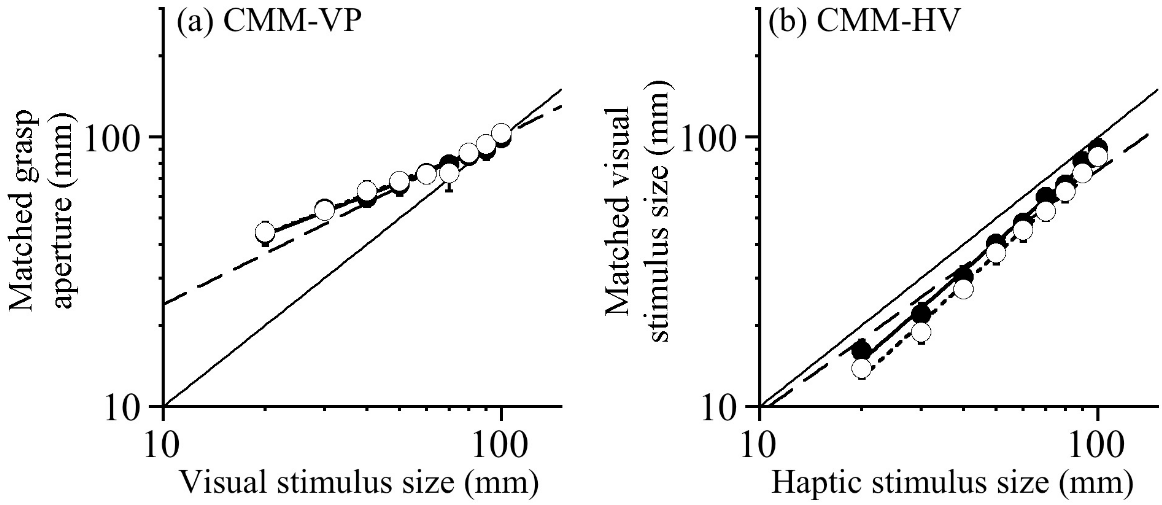

Figure 2: The results of CMM experiments. The results of CMM ((a), (b)) experiments. Data points indicate the average of 12 subjects, and error bars show ± 1 SD. Solid thin lines show functions with a slope of 1.0. (a) Open (○) and filled (●) circles show the matched grasp aperture as a function of the visual stimulus size for the line and circle stimuli, respectively. Dotted and solid lines are the best-fitting power functions obtained by the least-squares procedure. (b) Open (○) and filled (●) circles show the matched visual stimulus size as a function of the haptic stimulus size for the rectilinear- and cylindrical-block stimuli, respectively. Dotted and solid lines are the best-fitting power functions. Dashed lines in the two panels ((a), (b)) indicate the functions predicted by the model (see Eqs. (3) and (5) in the text).

4 Discussion

Our study found an asymmetry between the CMM-VP and CMM-HV functions. The ME and MP experiments consistently demonstrated that the visual perception of size was a linear function of physical size, whereas the haptic/proprioceptive perception of size was a nonlinear function of physical size, that is, a power function with an exponent of 1.6 for ME-H and 0.6 for MP-P. If the cross-modality matching was performed by a straightforward transformation of metric mediated by perceived magnitude, both of the CMM-HV and CMM-VP data would be a nonlinear function, which would be symmetrical with respect to a line with an exponent of 1.0. In CMM-HV, the nonlinear haptic magnitude would be transformed into a linear visual magnitude, then the exponent for the CMM-HV would be smaller than 1.0 (presumably 0.6=1/1.6). In CMM-VP, a linear visual magnitude would be transformed into the nonlinear proprioceptive magnitude, then the exponent for the CMM-VP would be larger than 1.0 (presumably 1.6). However, this was not the case. The assessment of object sizes from haptic perception to visual percepts produced a linear function, whereas the assessment of sizes from visual perception to grasp aperture produced a nonlinear function. This result may imply that, since the coding of object size is very different between visual and haptic modalities, the vision and haptic signals may not be transformed straightforwardly but may be coordinated by subsystems within each modality.

The asymmetry between the CMM-VP and CMM-HV functions supports our hypothesis of the existence of two subsystems within each modality: a vision-for-perception subsystem serving to produce visual magnitude of size and a vision-for-action subsystem serving to transform the visual signal into a signal for grasping; a haptic-for-perception subsystem serving to produce haptic magnitude of size and a haptic-for-visual-apprehension subsystem serving to transform haptic signal to visual representation. Our hypothesis led to the model shown in Fig. 3, which shows how coordination between vision and haptics can be performed and manifests its effect in cross-modality matching.

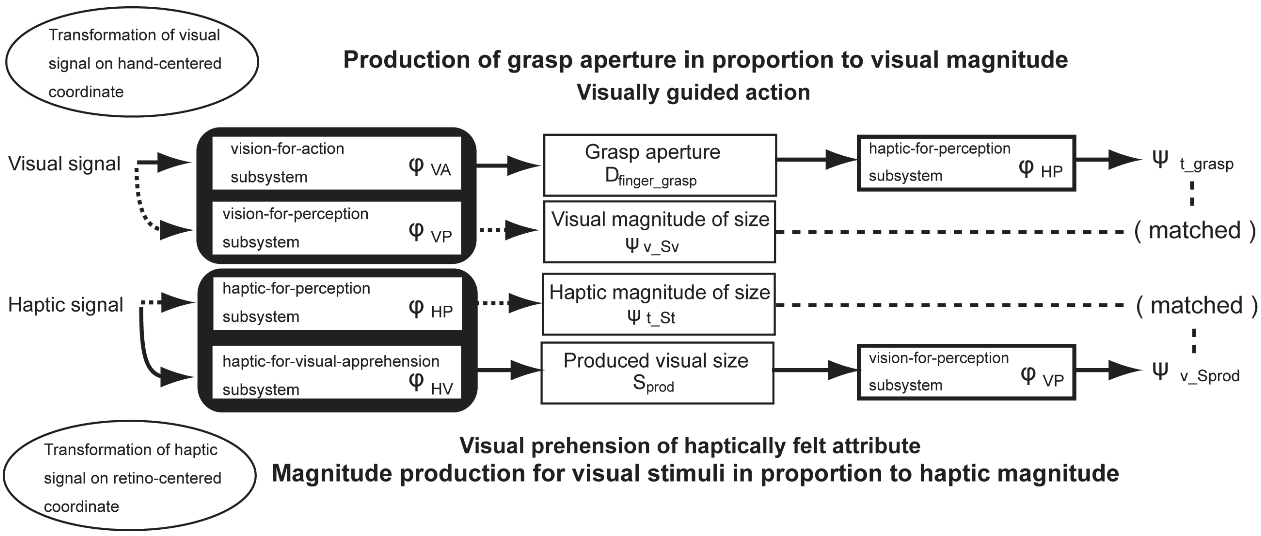

Figure 3: A model of the coordination between visual and haptic signals. See text for details.

The processing stream starting from ‘Visual signal’ (the upper part in Fig. 3) shows a case where the input modality is visual, that is, production of the grasp aperture in proportion to the visual magnitude (CMM-VP). In this case, the vision-for-action system transforms visual information into a signal for action to achieve a precise grasp (grasp aperture). From the results of the ME-V experiment (Fig. 1(a)), the visual system transforms the physical length, s, into the visual sensory magnitude, ψ_v, employing a function with an exponent of 0.9 (Table 1):

$$\psi_v = s^{0.9} \quad (1)$$

From the results of the ME-H experiment (Fig. 1(b)), the haptic system transforms the physical length, s, into the haptic sensory magnitude, ψ_t, evoked by a grasp aperture, that is, the spread between fingers, D_{finger}, employing an exponential function with an exponent of 1.6 (Table 1):

$$\psi_t = s^{1.6} = D_{finger}^{1.6} \quad (2)$$

Since the proportionality constant depends on the modulus used in the ME experiment, it is assumed to be zero for simplicity. In the CMM-VP experiment, the visually perceived object size is estimated by the grasp aperture, and the haptic sensory magnitude, ψ_{t_grasp}, produced by the grasp aperture (i.e., spread between the fingers, D_{finger}), is equated to the visual sensory magnitude, evoked by an object size of s_v; that is, $\psi_{t\_grasp} = \psi_{v\_Sv}$. From this, together with the relations described in Eqs. (1) and (2), the grasp aperture, D_{finger_grasp}, should be as follows:

$$D_{finger\_grasp} = \psi_{t\_grasp}^{(1/1.6)} = \psi_{v\_Sv}^{(1/1.6)} = s_v^{(1/1.6)} \quad (3)$$

Equation (3) represents the transformation of the visual sensory magnitude evoked by a stimulus size into a motor signal for the grasp aperture in a visually guided grasping action. Equation (3) predicts that the grasp aperture, produced so as to be equated to the visual magnitude, would be an exponential function of the physical size of a visual stimulus, s_v, with an exponent of 1/1.6 (= 0.625).

The processing stream starting from 'Haptic signal' (the lower part in Fig. 3) shows the case where the input modality is haptic, that is, the magnitude production for visual stimuli in proportion to the haptic magnitude (CMM-HV). In this case, the haptic-for-visual-apprehension subsystem proceeds to the transformation of haptic signals for the visual prehension of a haptic attribute of the size of an occluded object. In the CMM-HV experiment, the touch-perceived size is estimated as a visually equivalent size. From Eqs. (1) and (2), for a given physical length, s, the visual sensory magnitude, ψ_v, can be related to the haptic sensory magnitude, ψ_t, using the following equation (produced by a process of elimination of s in Eqs. (1) and (2)):

$$\psi_v = \psi_t^{(0.9/1.6)} \quad (4)$$

Equation (4) represents a possible way to coordinate a haptic metric signal with a visual metric signal in processing of haptic-for-visual-apprehension system. Applying Eq. (4) to the CMM-HV situation, the produced visual stimulus length, S_{prod}, so as to be equated to the haptic sensory magnitude, ψ_{t_St}, evoked by the physical length of a haptic stimulus, s_t, should be as follows:

$$S_{prod} = \psi_{v\_Sprod} = \psi_{t\_St}^{(0.9/1.6)} = (s_t^{1.6})^{(0.9/1.6)} = s_t^{0.9} \quad (5)$$

Therefore, in CMM-HV, the psychophysical function would be nearly linear and its exponent would be 0.9.

The dashed lines (Fig. 2(a), (b)) show the prediction based on our model, obtained using Eqs. (3) and (5), with the intercept parameters estimated employing a least-squares procedure.

As indicated, the differential properties in cross-modality matching between CMM-HV and CMM-VP can be well explained by our model.

In everyday life, we mostly commonly see an object first and are then faced with the task of shaping our grip to accurately reflect the object size, that is, visually guided action. The opposite transformation, therefore, has less frequent application. However, the nature of the vision-haptic coordination revealed by the asymmetry of cross-modality matching suggests that the coordination may be carried out in a principled manner by subsystems within each modality. When an object is first perceived visually and then by touch, the vision-for-action subsystem carries out coordinate transformation for visually guided motor commands so that visually guided grasping can be organized in the hand-centered coordinate. When an object is first perceived by touch and then visually, the haptics-for-visual-apprehension subsystem transforms the haptic attribute into a visual attribute in the corresponding visual receptive fields representing the visual space so that haptic information may be visually apprehended. The subsystems may serve to transform signals with different metric properties and frames of reference into those with a common frame of reference, and this enables comparison and evaluation of their reliability with a common frame of reference.

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対象の大きさマッチングにおける非対称性に基づく視・触覚協調に関する研究

大きさ知覚における視覚情報と触覚情報の協調過程について、magnitude estimation (ME) 法、magnitude production (MP) 法、cross-modality matching (CMM) 法による実験的検討を行った。ME 実験及び MP 実験の結果､視覚的大きさは刺激の物理的大きさの線形関数で記述できるが、触覚的大きさは非線形の特性を示すことが明らかとなった。また、視覚的に提示された刺激の大きさを触覚的に表現する視覚・触覚 CMM 実験の結果と、触覚的に提示された刺激を視覚的に表現する触覚・視覚 CMM 実験の結果は、逆数関係にない、即ち両属性の大きさ知覚は非対称性を示すことが明らかとなった。ME、MP、CMM 実験の結果は、視覚的な大きさ情報と触覚的な情報は、単純な変換過程で関係づけられるのではなく、視覚情報は把持のための運動情報に変換され、触覚情報は視覚情報に変換されることを示すものである。

キーワード：　大きさ知覚、視覚、触覚、属性間マッチング