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R-V Dynamics Illusion: Psychophysical Phenomenon Caused by the Difference between Dynamics of Real Object and Virtual Object

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Abstract
In Mixed-Reality (MR) space, it appeared that the sense of weight can be affected by a MR visual stimulation with a movable portion. We named this psychophysical influence caused by the difference between dynamics of the real object (R) and the virtual object (V) movement, the "R-V Dynamics Illusion." There are many combinations of experiments that can be conducted. Previously, we conducted experiments of the case where the real object is rigid and the virtual object is dynamically changeable. In this paper, we conducted experiments of the case where the real object is liquid and both the real and the virtual objects are dynamically changeable. The results of the experiments showed that the subjects sensed weight differently when virtual object with a movable portion is superimposed onto a real liquid object.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems – Artificial, augmented, and virtual realities

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1. Introduction

By combining multiple technologies for providing sensation, rather than dealing with the five human senses independently, research that focuses on complementing and providing sensations that are difficult to reproduce, and research concerning illusions that occur due to the interplay between multiple senses, has gained considerable attention. For example, Pseudo-Haptics is a remarkable phenomenon in which there is interaction between the visual and tactile/haptic senses, and when a discrepancy occurs between physical movement and the visual stimulation that is reflected, the illusion of an artificial tactile/haptic sense occurs [LCK*00]. Thus, by daring to create a discrepancy between the modality of each sense, multiple perceptions influence each other, and create illusory phenomena that do not occur with independent senses.

In our research group, we have studied interaction and complementary effects between the visual sense and tactile/haptic sense using MR technology [OKSH12, HKSH11]. Through the use of MR technology, in which it is possible to combine the real world and virtual world in real time, phenomena that occur in the real world can be superimposed on CG (Computer Graphics) image, and a discrepancy between the visual sense and tactile/haptic sense can be intentionally produced. We have conducted tests and analysis in a systematic way in regard to the kind of influence visual stimulation (hereafter, "MR visual stimulation") has on the visual sense. Through this, we have discovered various illusions, such as the "Shape-COG Illusion" [OKSH12], in which an illusion of the center of gravity is provided by MR visual stimulation for a center of gravity that differs from the actual object and the "Dent-Softness Illusion" [HKSH11], which is an illusion of hardness gained by providing MR visual stimulation of hardness that differs from the actual object. We have, therefore, gained a significant amount of objective knowledge about these illusory phenomena.

In our study of the Shape-COG Illusion, we made the actual objects targeted rigid objects. However, during the research process, questions arose regarding how it would be perceived if the actual object or its inner content was movable, or there existed CG animation in which the contents of the actual object was movable through MR visual stimulation. We conducted a test in regard to what effect there would be on visual and haptic sense if we superimposed a virtual object that could cause the perception of dynamic change within the object in relation to a rigid object. This was shown to have a significant influence on the perception of the weight of the object. To that end, we named the influence that the different movement states of the real object (R) and virtual object (V) would have on the perception of

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movement of the actual object through the visual sense as "R-V Dynamics Illusion" [HKSK14, HSSK14-1, HSSK14-2].

Until now, we have confirmed the occurrence of the same illusion, which was limited to cases where the actual object is a rigid object. In this paper, we add the dynamic condition that liquid is enclosed within the actual object, and verify the influence of differences in the movement states on the perception of weight. We can also see how powerful the influence of this illusion is by comparing the real liquid and the rigid object with superimposed liquid CG. Furthermore, we observe the phenomenon of this illusion, by measuring the muscle potential and performing a kinesiological analysis.

2. Related Works

Known illusions include the previously described Pseudo-Haptics [LCK*00], which is an illusion occurring due the interoperability between the visual and haptic senses, and the Size-Weight Illusion [Cha91]. Pseudo-Haptics is a form of illusion that can prevent tactile and haptic sensations by operating only on visual stimulation, even without a physical haptic presentation device, and provides object hardness, surface texture, viscosity etc. [LBE04]. This phenomenon, which provides kinesthetic sensation by operating on the visual sense alone, is considered to be closely related to this study.

The Size-Weight Illusion is a phenomenon in which, depending on the extent of its volume, objects with identical mass will feel as if they are different weights. This illusion exists even without visual information, but it has been shown that its effects are more significant when visual stimuli are present [EL93]. Rock *et al*. [RV67] have shown that when the size of a cube held in the hand of the test subject is magnified, the cube, which looks bigger, will feel lighter. In addition, there is also a known phenomenon where the color of the object will influence the perception of its weight [AS76]. This study also deals with the illusion of weight perception; however, the phenomenon in which the perception of weight changes simply by visually superimposing dynamic changes on the contents of the actual object onto said object without actually touching it, is not known.

On the other hand, methods have been proposed, through the use of interoperability and complementary traits between the visual and haptic senses, for providing visual sense fluctuations within the actual object with a high degree of reality. This can be performed through the use of a simple device. For example, Minamisawa *et al*. [MFK*07] focuses on dynamic changes within the object, and proposes a method to present the mass and internal dynamics of a virtual object using a kinesthetic presentation device. In contrast, in this study, we have confirmed what kinds of changes occur in human perception when changing only the internal dynamics with visual information.

Apart from our study, research investigating the influence of MR visual stimulation on kinesthetic force has already been conducted by several others [OKSH12, HKSH11, HKSK14, HSSK14-1, HSSK14-2]. For example, Nakahara *et al*. [NKO07], using MR technology and HMD, have reported that perception of objects can be modified by superimposing cornered virtual objects and rounded virtual objects on the actual object. It is also reported that stiffness of objects can be modified by changing visual stimulation [BNTH14, KBN*14, PDK15]. Furthermore, Ban *et al*. [BNF*13] clarified that the color of CG images superimposed on the actual object influences weight perception. However, most of the research concerning the effects of MR stimulation on the haptic sense focuses on static information such as object texture and external appearance.

We aim to clarify what kind of influence there is on human kinesthetic perception when dynamically changing the MR visual stimulated according to the movement of the grasped object, or in other words, when presenting different movement states between the actual object and the superimposed CG image.

In this paper, the conditions for kinesthetic and haptic sensation areas (actual object) are set for cases involving both rigid objects and objects with liquid introduced, and we aim to confirm what influences there are on human kinesthetic and haptic perception by changing the movement states internal to the object through visual stimulation.

3. Objectives and Preparation

3.1 Objectives

In this study, we confirm the influence on kinesthetic and haptic perception for cases involving dynamic change where the internal area of the actual object is a rigid shape and where liquid has been introduced to the actual object. Specifically, we confirm and analyze the following.

(1) Is the illusion of weight produced even when a dynamic change such as liquid is introduced to the contents of the actual object?

(2) When the CG movement for the liquid inside differs between the actual object and virtual object, what influence does that have on the perception of weight?

(3) Measure the muscle potential and object acceleration when performing an action such as shaking the object, and observe the phenomenon of the illusion.

3.2 Preparations

Experiment environment

Figure 1 shows the configuration of the MR system used for the experiment. In this experiment, a video see through-type HMD (Head Mounted Display) and MR Platform System was used. The position posture information for the head section of the test subject and the actual object were acquired using magnetic sensors. The sampling rate of the magnetic sensor is 120Hz, and the HMD is operating at 30fps. In order to gain consistency in the angle at which the grasped object is shaken, angle information via the magnetic sensors is used, and when horizontal at 0°, the test subject is notified with a beep noise when leaning 30° or more left or right. When this noise is made, they are directed to shake immediately in the opposite direction, so the time in which the beep sound is made is very short.

Actual object used

For the actual object grasped by the test subject, we used an acrylic case with dimensions of width 165 x depth 80 x height 90 mm and with a handle attached. Furthermore, by introducing a weight to the case, we were able to adjust its weight to the same weight as when pouring water up to 45 mm high inside the case (750 g). The case in which water was added was the same size, and by inserting water up to the 45 mm mark, the uniform weight of 750 g was achieved (Figure 2).

MR visual stimulation

The virtual container presented as MR visual stimulation had the same dimensions as the actual object: width 165 x depth 80 x height 90 mm. The liquid volume within the virtual container used in the experiment had a water surface position of half the container at 45 mm. Furthermore, the liquid section was light blue while the section without any liquid was colored white (Figure 3). In the experiment, the test subject shook the container left and right, presenting an image of the liquid inside moving left and right. We employed a simplified model that mimics the swaying of the liquid, without a detailed representation such as waves or splash (Figure 4). C is a value affecting the acceleration of the liquid. The viscosity of liquid is perceived higher as the value C increases. In a preliminary experiment, the subjects felt our liquid model like the water when the value C was approximately 0.98 (deg/s2).

4. Experiment

4.1 Objective and Conditions

Based on the experiments, we clarified what effect differences in the movement state of the actual object and virtual object had on weight perception.

We used Thurstone's paired comparison method for the evaluation. The actual objects used in the experiment were the two types of rigid objects and liquid shown in Figure 2. The conditions for the virtual object were two types; the enclosed CG liquid is moving and not moving. In addition to these, in order to provide a standard stimulation in which there was no influence from the visual stimulation of the virtual object, there were attempts for both the rigid object and liquid conditions where the CG was not superimposed. Furthermore, attempts were made under the condition of visually confirming the movement of the liquid in the actual object. By combining these conditions, the seven patterns of experiments P1-P7 were performed (Table 1).

4.2 Procedure

The experiment procedure was based on the Thurston method, and selection was made based on which felt heavier. The test subject did not need to waver between three or more selections and a method with a simple psychological scale was used. The number of attempts was ${}_7C_2$ = 21 times per person, and there were 11 test subjects (10 males and 1 female in their 20's). At the time of the experiment, and they were instructed to adopt the posture shown in Figure 5 and control the swinging action. The posture involved grasping the actual object from a standing position with the elbow bent at a 90 degree angle. The shaking action was

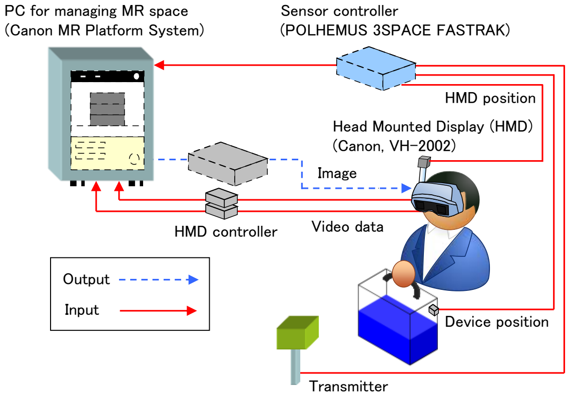


Figure 1: *System configuration*

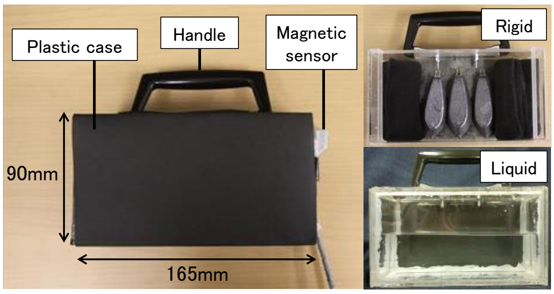


Figure 2: *Real object used in experiments*

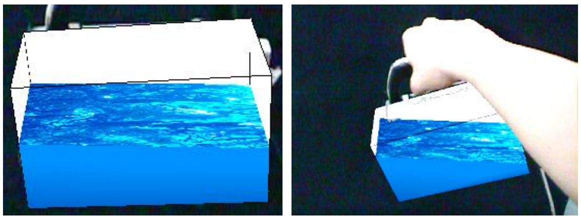
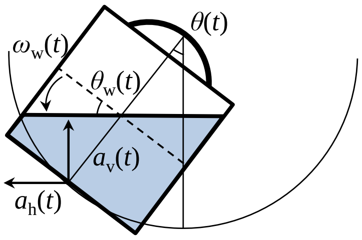


Figure 3: *MR visual stimulation used in experiments*



$$a_w(t) = -(C - a_v(t))\cos\theta(t) + a_h(t)\sin\theta(t) \qquad (1)$$

$a_w(t)$	Angular acceleration of a liquid
$\omega_w(t)$	Angular velocity of a liquid
$\theta_w(t)$	Angle of a liquid
$\theta(t)$	Angle of object
$a_v(t)$	Acceleration of object (vertical direction)
$a_h(t)$	Acceleration of object (horizontal direction)
C	Acceleration value

Figure 4: *Simplified model of virtual liquid movement*

aligned to the action of a metronome (100BPM) and they were instructed to shake within a fixed range of approximately 30 degrees left and right. The test subjects were given sufficient opportunity to practice in advance so they could perform the action as directed. The action was repeated at a speed of 100 round trip swings/minute for three seconds (five round trips). The test procedure is as follows.

(1) The test subject puts on the HMD.

(2) Two types are selected at random from the seven types of presented patterns (Table 1).

(3) One of the two types of patterns chosen in (2) is presented to the test subject.

(4) The test subject grasps the actual object in the determined posture (state in which the elbow is bent 90 degrees), and swings the object left and right in accordance with the metronome tempo (100BPM) (for three seconds).

(5) (3) and (4) are repeated in the same way for the other CG selected in (2).

(6) Ask the subject to answer which felt heavier after trying both the first and second time.

(7) In order to eliminate the effects of muscle weakness, allow subject to rest for approximately one minute.

(8) Repeat (2) - (7) for remaining combinations.

Table1: *Variety of MR visual stimulation used in experiments*

Pattern	Real object	Superimposed CG
P1	Rigid form	None (Watch a black case)
P2		Not moving
P3		Moving
P4	Liquid (Water)	None (Liquid is not visible)
P5		Not moving
P6		Moving
P7		None (Liquid is visible)

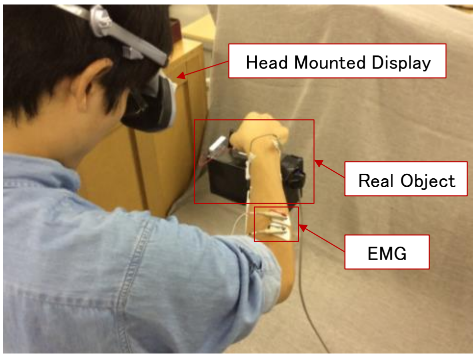


Figure 5: *Experimental scene*

4.3 Results of the Experiment

The results of the experiment are as shown in Figure 6. The two number lines in the diagram represent the psychological scale of the weight for each presented pattern. The more the numerical value decreases, the heavier the test subject feels the grasped object to be. Furthermore, it was confirmed using a sign test that these results are significant. We can learn the following from the results of the test.

(i) For the condition involving no CG, the liquid is perceived as being lighter than a rigid object.

(ii) As in the case of the rigid body, even when the contents of the actual object is liquid, in cases where the liquid is presented as moving it is perceived as lighter than when it is not presented as such.

(iii) The haptic sense relationship in actual space and the influence of the visual sense are expressed in an additive way.

(iv) Although the influence of color can be considered, the effect of swaying is considered to be more significant.

For (i), P4 (Liquid, None (Liquid is not visible)) is perceived as lighter than P1 (Rigid, None (Watch a black case)). For P1 and P4, CG is not superimposed, and the influence of visual stimulation was excluded, with a black case being shaken. As P4 was perceived as lighter than P1, we can see that when there is no influence from visual stimulation, in cases where the contents of the actual object is liquid, it is perceived as lighter. Furthermore, when comparing P7 (Liquid, None (Liquid is visible)) and P4, P7 was perceived as being lighter. P7 involved the condition of swinging the object while actually watching the movement of the liquid in the real object. Therefore, we can see that it is the presence of visual stimulation rather than hap-

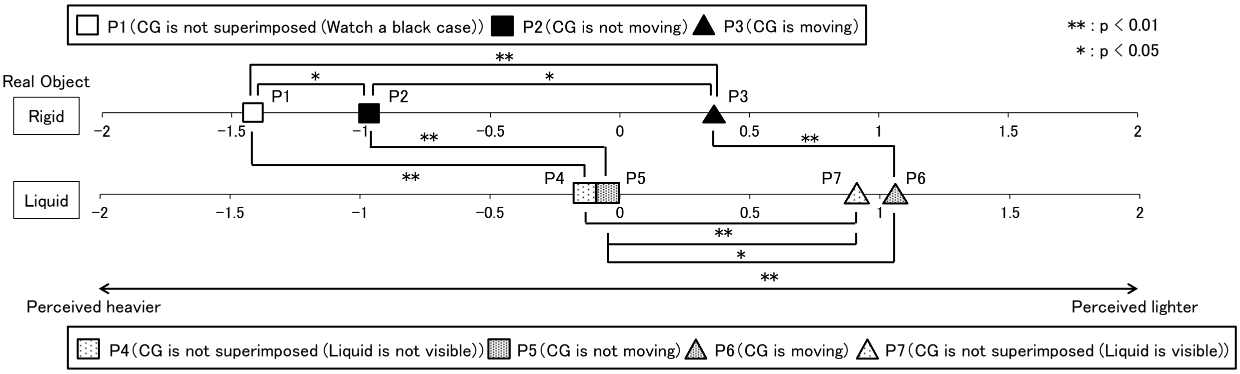


Figure 6: *Result of experiment*

tic sensation that causes it to be perceived as lighter.

In (ii), P6 (Liquid, Moving) was perceived as being lighter than P5 (Liquid, Not moving). This enabled us to confirm in the same way as the preceding research, that even when the contents of the actual object is liquid, this will influence weight perception in the same way. Furthermore, in (iii), P6 (Liquid, Moving) was perceived as lighter than P3 (Rigid, Moving). From the results of (i), we can see that, for visual perception conditions, liquid (P4) is perceived as lighter than rigid (P1), but with the haptic relationship as it is in actual space, the influence of visual stimulation is expressed in an additive way.

In (iv), the actual object in P1 (Rigid, None (Watch a black case)) is a black case and the virtual object in P2 (Rigid, Not moving) has the section in which there is no liquid colored white. In the study by Ban *et al*., it is suggested that there is a trend for white to be perceived as being lighter than black [BNF*13]. In this experiment, it was similarly considered that color has an effect on weight perception. However, this was not significant in the case of P4 (Liquid, None (Liquid is not visible)) and P5 (Liquid, Not moving). Even in the liquid conditions, there is the possibility of being influenced by color, but the influence of movement on the virtual object is more significant, and it was believed to be lighter.

5. Analysis of Muscle Potential

5.1 Objective and Conditions

Under the R-V Dynamics Illusion, physical kinesthetic sensation could also be influenced by visual stimulation. Therefore, we observed and analyzed muscle potential of the arm under the illusion. The conditions of observations are similar to the previous experiment.

5.2 Method of Measuring Muscle Potential and Acceleration

As the movement of shaking the actual object left and right involve supinator and pronator movements, we measured the supinator and pronator muscles that work during these movements. In order to measure as shown in Figure 7, we used disposable electrodes. The electrodes were attached with a distance of 25 mm allowed between each, and the grounding electrode was placed on the styloid process of the radius. The analog signal drawn from the surface electromyograph was retrieved to a PC at a sampling frequency of 500 Hz.

In this study, in order to analyze the amount of pronator and supinator muscle muscular activity when swinging the grasped object, we used %MVC (Maximal Voluntary Contraction), which provides an index for the degree of activity drawn from the amplitude information. %MVC calculates the measured electromyogram (EMG) in relation to the muscle potential when performing the maximum voluntary contraction. The formula for the calculation is shown in (2).

$$\%\mathrm{MVC} = \frac{\text{Measured muscle potential (EMG)}}{\text{Maximal voluntary contraction (MVC)}} \times 100 \qquad (2)$$

The muscle potential during the maximal voluntary contraction (MVC) of the supinator and pronator muscles measures, separately, the maximum values for voluntary muscle contraction. Analysis of muscle potential, after performing full wave rectification on the waveform obtained from the electromyography, normalizes this using the MVC measured for each test subject to calculate %MVC. %MVC increases when the weight of the actual object physically increases.

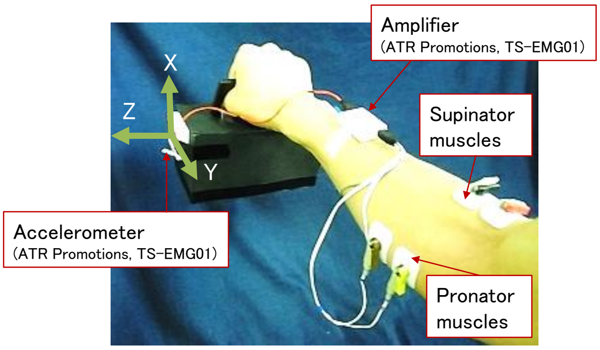


Figure 7: *Electromyograph and accelerometer*

In addition, acceleration was measured at the same time as muscle potential. As shown in Figure 7, an accelerometer is attached to the side of the grasped object. The acceleration in the Z axis direction within the diagram is used for the analysis and this is retrieved to a PC at a sampling frequency of 500 Hz.

5.3 Procedure of the Observations

Conditions for seven patterns (Table 1) are presented to the test subject (5 males in their 20's). Similar to 4.2 as the swinging movement is controlled, they were allowed to practice sufficiently until they could perform the action in the instructed way, in terms of the swing tempo and posture. So that the amount of muscle activity was not affected by fatigue levels, the attempts were set to a speed of 100 round trips per minute for three seconds (five round trips). The procedure was as shown below.

(1) The test subject put on the HMD and electrodes for measuring muscle potential.

(2) One of the seven types of presented patterns was selected at random and presented to the test subject.

(3) The test subject holds the actual object in the predetermined position and swings the object left and right in accordance with the tempo of the metronome (100 BPM).

(4) The subject stays still for three seconds after performing (3).

(5) Repeat (3) and (4) three times.

(6) In order to exclude the effects of muscle fatigue, rest for one minute.

(7) Repeat (2) - (6) for the remaining patterns.

5.4 Results of the Observations

The %MVC average values

Based on the results of the observations, we calculated the average values of %MVC for each presented pattern. The average values of %MVC for each presented pattern are shown in Figure 8. Furthermore, from the results of ANOVA, significant differences were seen under each condition (supinator: [F(8, 900)=33.6, $p < 0.01$], pronator: [F(8, 900)=13.8, $p < 0.01$]). Here, we perform multiple comparisons based on the Bonferroni method, and confirmed these significant differences. The significance within the figure was confirmed for both supinator and pronator groups. We can learn the following from the observation of muscle potential.

(i) Supinator and pronator both exhibit the same trends.

(ii) When there was no CG, there was no difference in the amount of muscular activity when shaking the liquid or a rigid body.

(iii) Even when the content of the actual object is a rigid body or liquid, the amount of muscular activity decreases when the movement of liquid CG is presented.

(iv) Even when the contents of the actual object is a rigid body or liquid, when there is no CG, no difference can be seen in the amount of muscular activities under the condition where CG is not moving.

(v) The amount of muscular activity is easily influenced by dynamic visual stimulation.

From (i), as the average value of supinator and pronator %MVC show the same trends, the amount of muscular activity shown below is included in both supinator and pronator groups.

In (ii), there was no significant difference in muscular activity between P1 (Rigid, None (Watch a black case)) and P4 (Liquid, None (Liquid is not visible)). That is, P4 was perceived as being lighter than P1, but the weight of the liquid and the rigid shape were the same, and the differences between the liquid and rigid forms did not influence the amount of muscular activity.

In (iii), P6 (Liquid, Moving) has a decreased amount of muscular activity compared to P5 (Liquid, Not moving). The difference between P2 (Rigid, Not moving) and P3 (Rigid, Moving) showed the same results as the preceding research, and for both rigid and liquid, when there were dynamic changes in visual stimulation, this influenced the amount of muscular activity.

In (iv), no difference was seen in amount of muscular activity between the conditions of P4 (Liquid, None (Liquid is not visible)) and P5 (Liquid, Not moving). This was the same for the conditions of P1 (Rigid, None (Watch a black case)) and P2 (Rigid, Not moving). From this, there was influence from color or the CG case, but the amount of muscular activity is not affected.

With (v), from the results of (ii) - (iv) , we can say that with only the difference between rigid forms and liquid inside the actual object, the influence on the amount of muscular activity is low, and when the movement of CG liquid is presented, there is a major effect on the amount of muscular activity. It is possible that this is because, as the movement of CG liquid in relation to the movement of shaking due to visual stimulation, there is an easing of force in accordance with the visual stimulation. Therefore, it is possible that the level of muscular activity reflects exertion and easing of force based on the visual stimulation. It is also reported that exertion of force has an impact on the perception of weight, and from this observation as well, it is possible that the exertion of force has an influence on the perception of weight [KKD06].

The %MVC time variation

In the observations, acceleration was measured at the same time as muscular potential. By measuring the acceleration, it is possible to record the movement state of the shaking action. By observing changes in the movement state and muscular potential, we can examine the phenomenon by which the R-V Dynamics Illusion is generated.

Figure 9 shows typical output of the %MVC for supinator and pronator for one round-trip of shaking action. We

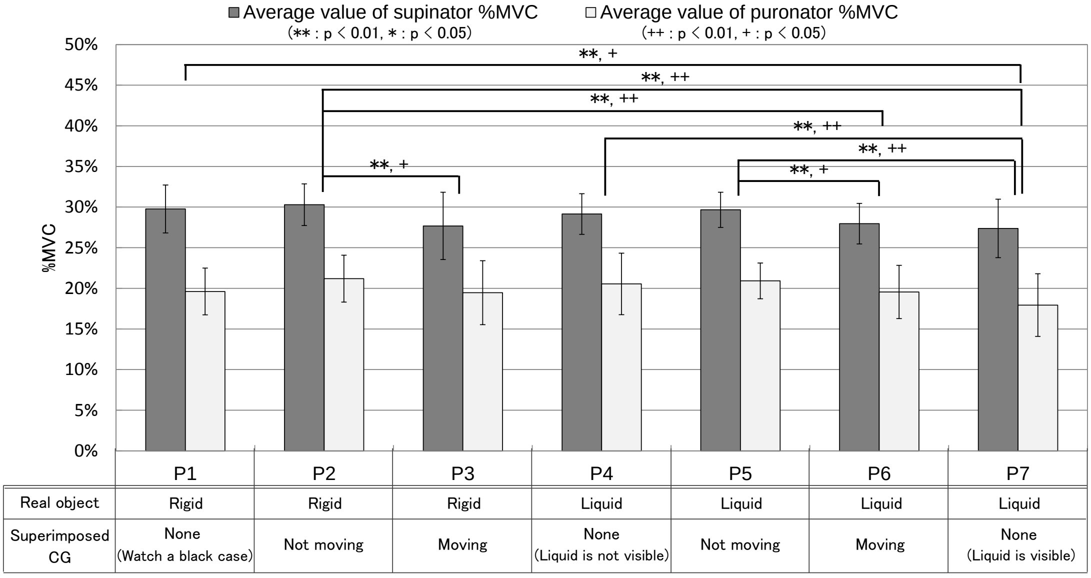
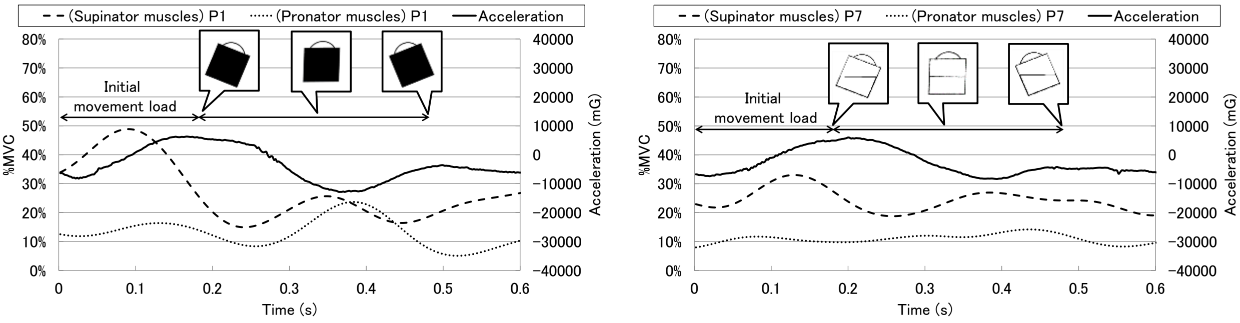
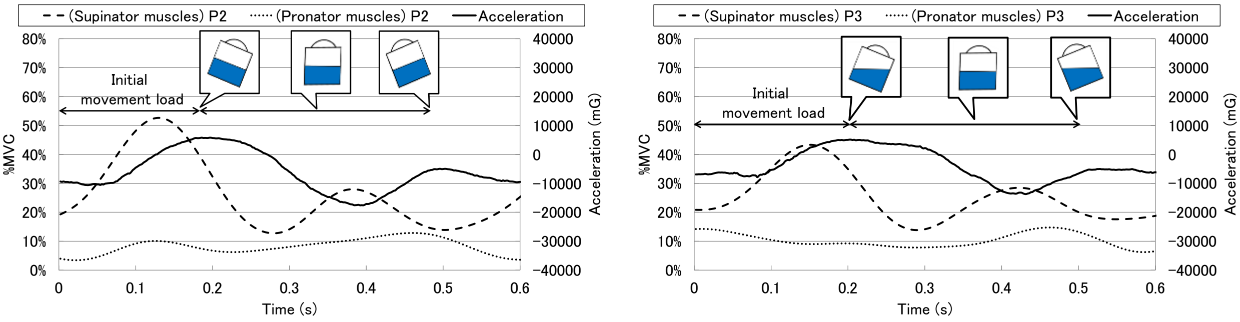


Figure 8: *Average value of the %MVC*



(a) P1 (Real object is rigid and CG is not superimposed)

(b) P7 (Real object encloses liquid, and CG is not superimposed)



(c) P2 (Real object is rigid and CG doesn't move)

(d) P3 (Real object is rigid and liquid CG moves)

Figure 9: *Time variation of the %MVC*

can learn the following from the observations.

(i) The amount of muscular activity reaches its maximum level during the initial movement load.

(ii) The maximum amount of muscular activity at the initial movement load fluctuates based on visual conditions. Furthermore, there is a lower amount of muscular activity for the initial movement load, when the movement of liquid is presented.

In (i), the movement state of the shaking action can be observed from the values measured using the accelerometer. Muscular activity shows the most significant increase at the start of the initial movement load. This showed the same trend for all of the conditions. Furthermore, as shown in the results for (ii), the maximum amount of muscular activity during the initial movement load showed different trends depending on the conditions (e.g. Figure 9: P1 > P7, P2 > P3). In the studies by Hamilton and Taima *et al.*, differences were confirmed in the amount of muscular activity according to the weight at the initial movement load [HJF*07, TBN*14]. The differences that occurred at the time of initial movement load in this study, therefore, may influence the perception of weight.

Furthermore, there is a high possibility that the perception of weight at the initial movement load primarily used information surmised from the visual stimulation, and significantly expressed the influence of visual stimulation.

6. Conclusions

In this paper, we have shown, in addition to the R-V Dynamics Illusion when the contents the actual object is rigid as confirmed in the preceding studies, that even when the contents of the actual object is liquid, through the presentation of a dynamic visual stimulation, the object can be perceived as being light. More specifically, the following findings were obtained.

(a) In the conditions where the content of the actual object was rigid or liquid, dynamic visual stimulation affected the perception of weight and amount of muscular activity; it is perceived as lighter and the amount of muscular activity decreases when the movement of CG liquid is presented.

(b) It is possible that the exertion or easing of force due to dynamic visual stimulation has an influence on perception of weight.

(c) The amount of muscular activity most increases during the initial movement load, and the amount of this increase changes according to the visual stimulation.

Based on these results and observations, the occurrence of R-V Dynamics Illusion was confirmed when the contents the actual object was either rigid or liquid. Liquid was perceived as lighter than the rigid form, and the influence of the visual stimulation was additive.

Furthermore, the observations of amount of muscular activity suggested the possibility that the exertion or easing of force during initial movement load influenced the perception of weight in particular. Moving forward, we plan to confirm that cause of this phenomenon, as well.

References

[LCK*00] LECUYER A., COQUILLART S., KHEDDAR A., RICHARD P., COIFFET P.: "Pseudo-haptic feedback: can isometric input devices simulate force feedback?," *IEEE* VR 2000, pp. 83 - 90, 2000.

[OKSH12] OMOSAKO H., KIMURA A., SHIBATA F., HIDEYUKI T.: "Shape-COG Illusion: Psychophysical influence on center-of-gravity perception by mixed-reality visual stimulation," *IEEE* VR 2012, pp. 65 - 66, 2012.

[HKSH11] HIRANO Y., KIMURA A., SHIBATA F., HIDEYUKI T.: "Psychophysical influence of mixed-reality visual stimulation on sense of hardness," *IEEE* VR 2011, pp. 51 - 54, 2011.

[HKSK14] HASHIGUCHI S., KATAOKA Y., SHIBATA F., KIMURA A.: "Further analysis of the R-V Dynamics Illusion on sense of weight," IDW 2014, pp. 1545 - 1546, 2014.

[HSSK14-1] HASHIGUCHI S., SANO Y., SHIBATA F., KIMURA A.: "R-V Dynamics Illusion in mixed reality space," *IEEE* Haptics Symposium 2014, 2014.

[HSSK14-2] HASHIGUCHI S., SANO Y., SHIBATA F., KIMURA A.: "R-V dynamics illusion: Psychophysical influence on sense of weight by mixed-reality visual stimulation of moving object," HCII 2014, pp. 55 - 64, 2014.

[Cha91] CHARPENTIER A.: "Experimental study of some aspects of weight perception," *Archives de Physiologie Normales et Pathologiques*, Vol. 3, pp. 122 - 135, 1891.

[LBE04] LECUYER A., BURKHARDT J., ETIENNE L.: "Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures," CHI 2004, pp. 239 - 246, 2004.

[EL93] ELLIS R. R., LEDERMAN S. J.: "The role of haptic versus visual volume cues in the size-weight illusion," *Attention, perception & psychophysics*, Vol. 53, No. 3, pp. 315 - 324, 1993.

[RV67] ROCK I., VICTOR J.: "Vision and touch," *Scientific American*, Vol. 216, pp. 96 - 104, 1967.

[AS76] ALEXANDER K. R., SHANSKY M. S.: "Influence of hue, value, and chroma on the perceived heaviness of colors," *Attention, Perception, & Psychophysics*, Vol. 19, No. 1, pp. 72 - 74, 1976.

[MFK*07] MINAMIZAWA K., FUKAMACHI S., KAJIMOTO H., KAWAKAMI N., TACHI S.: "Gravity Grabber: Wearable haptic display to present virtual mass sensation," SIGGRAPH 2007 emerging technologies, No. 8, 2007.

[NKO07] NAKAHARA M., KITAHARA I., OHTA Y.: "Sensory property in fusion of visual/haptic cues by using mixed reality," *IEEE* World Haptics 2007, pp. 565 - 566, 2007.

[BNTH14] BAN Y., NARUMI T., TANIKAWA T., HIROSE M.: "Controlling perceived stiffness of pinched objects using visual feedback of hand deformation," *IEEE* Haptics Symposium 2014, pp. 557 - 562, 2014.

[KBN*14] KOKUBUN A., BAN Y., NARUMI T., TANIKAWA T., HIROSE M.: "Representing normal and shearing forces on the mobile device with visuo-haptic interaction and a rear touch interface," *IEEE* Haptics Symposium 2014, pp. 415 - 420, 2014.

[PDK15] PARINYA P., DAISUKE I., KOSUKE S.: "SoftAR: Visually manipulating haptic softness perception in spatial augmented reality," *IEEE Trans. on Visualization and Computer Graphics 2015*, 2015.

[BNF*13] BAN Y., NARUMI T., FUJII T., SAKURAI S., IMURA J., TANIKAWA T., HIROSE M.: "Augmented Endurance: Controlling fatigue while handling objects by affecting weight perception using augmented reality," CHI 2013, pp. 69 - 78, 2013.

[KKD06] KOIKE Y., KIM J., DUK S.: "Role of stiffness in weight perception," *Japanese Psychological Research*, Vol. 48, No. 3, pp. 174 - 187, 2006.

[HJF*07] HAMILTON A. F., JOYCE D. W., FLANAGAN J. R., FRITH C. D., WOLPERT D. M.: "Kinematic cues in perceptual weight judgement and their origins in box lifting.," *Psychological Research*, Vol. 71, No. 1, pp. 13 - 21, 2007.

[TBN*14] TAIMA Y., BAN Y., NARUMI T., TANIKAWA T., HIROSE M.: "Controlling fatigue while lifting objects using pseudo-haptics in a mixed reality space," *IEEE* Haptics Symposium 2014, pp. 175 - 180, 2014.