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Augmented Cross-modality: Translating the Physiological Responses, Knowledge and Impression to Audio-visual Information in Virtual Reality

Yutaro Hirao and Takashi Kawai
Department of Intermedia Art and Science, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo, 169-0072, Japan
E-mail: yutaro-hirao@suou.waseda.jp

Abstract. *This paper proposes the method of interaction design to present haptic experience as intended in virtual reality (VR). The method that we named "Augmented Cross-Modality" is to translate the physiological responses, knowledge and impression about the experience in real world into audio-visual stimuli and add them to the interaction in VR. In this study, as expressions for presenting a haptic experience of gripping an object strongly and lifting a heavy object, we design hand tremor, strong gripping and increasing heart rate in VR. The objective is, at first, to enhance a sense of strain of a body with these augmented cross-modal expressions and then, change the quality of the total haptic experience and as a result, make it closer to the experience of lifting a heavy object. This method is evaluated by several rating scales, interviews and force sensors attached to a VR controller. The result suggests that the expressions of this method enhancing a haptic experience of strong gripping in almost all participants and the effectiveness were confirmed.* © *2018 Society for Imaging Science and Technology.*
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1. INTRODUCTION

In recent years, we can see and touch digital information with reality due to the development of Head Mounted Display (HMD), stereophonic technology. Thus, there is a problem of how to make the quality of experience in the interaction with virtual objects more realistic. This becomes an active area of research especially in the field of force feedback and tactile sensation, called Haptics [1].

For example, grounded force feedback display typified by PHANToM [2] and SPIDAR [3], Cybergrasp [4] and exoskeleton force feedback display such as Nagawara's one [5] are based on the approach that aims to present force feedback by calculating and mechanically reproducing physical force which is produced in the interaction with virtual objects. There is another approach that aims to present target feedback that is not physically the same output as real one by using perceptual illusion from human cognitive characteristics. There are various studies in this approach such as using Pseudo-haptics [6–11], using electrical stimulation [12] and using vibrator [13].

Among these approaches, many recent studies are being done especially using the method of cross-modal integration. The reason is that its structure is not overly complex and it provides the benefit of allowing users to move freely and comparatively simple system without hardware problems such as maximum output of motor, weight, latency and spatial resolution. For instance, both studies of Taima et al. [7] and Rietzler et al. [8, 9] propose the method presenting weight sense or reaction force by making a gap between the movement of real body and virtual body. Furthermore, the studies of Azmandian [14], Matsumoto [15] and Nagao [16] enable a user various actions in virtual reality (VR) though space or resources in real are limited by changing the correspondence relation between actual body movement and virtual one. Thus, the effectiveness of presenting a haptic experience by integrating embodiment into VR and changing it in VR is becoming clearer. In addition, it is assumed that this approach is feasible for immersive VR using HMD because of its high flexibility of audio and visual expression.

1.1 *Problem*

As one of the problems in the method presenting haptic feedback by using cross-modality described above, the problem lies in the fact that the haptic experience may have large individual differences depending on the degree of expressions and make users feel discomfort or other unintended sensation. For example, this is shown in our preliminary experiment in which we evaluated a haptic illusion in VR using cross-modality. The method is presenting various weight senses when a user lifting a virtual object in VR by delaying virtual object (and hand model) following his or her hand or by increasing the distance between the hand and the virtual object. The result suggests that participants significantly felt heavier as the gap became larger and can perceive multistage weight of the virtual object by both approaches. However, the larger the gap is, the larger the individual differences are. Furthermore, some participants commented that they felt inertial force, viscosity or the speed of movements itself instead of the sense of lifting a heavy object. It is assumed that one of the factors of this phenomenon is that participants who could not feel the sense of lifting a heavy object by cross-modality recognize the expression of delay or offset as different from the intended context.

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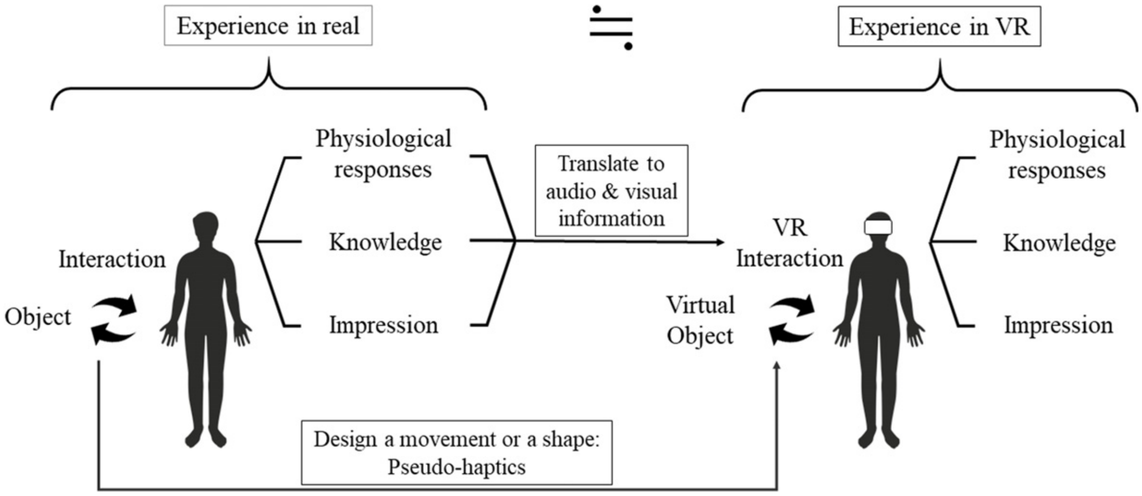

Figure 1. The conceptual diagram of augmented cross-modal system.

2. OBJECTIVE

It is suggested by several experiments [17–19] that personal experience and knowledge tend to affect haptic experience presented by cross-modality. Therefore, there is a possibility that the quality of the haptic experience is changed and enhanced, and becomes closer to one of the real experiences by translating the physiological responses, knowledge and impression about the target experience in real world into audio-visual information and adding it to the interaction in VR. Whereas conventional approaches using cross-modality aim to make the visual expression in VR closer to the real one, the method proposed here focused on making users evoke their past experience, knowledge and impression related to the target experience through designed expressions in VR. Thus, it does not matter how real the expression is and the expression can be unique in VR. We named the cross-modal illusion by this approach "Augmented Cross-Modality."

In this research, as expressions for presenting the experience of gripping an object strongly and lifting a heavy object, we design a hand tremor, strong gripping and increasing heart rate. Only with the conventional pseudo-haptic method using a gap between virtual body movements and actual movements, it is possible that haptic experience might have diversity such as inertial force, viscosity or just slow. In contrast, by adding the augmented cross-modal expressions described above, the haptic experience is expected to be unified into the experience of strong gripping and lifting a heavy object more than with just delay.

Therefore, in this paper, the main objective is to evaluate the effect of augmented cross-modal expressions on the quality of the haptic experience in VR. More specifically, the first objective is to evaluate whether the augmented cross-modal expressions of strain while lifting enhance the sense of strong gripping of the object, and the second is to evaluate if these expressions change the quality of the total haptic experience and as a result, make it closer to the experience of lifting a heavy object than just delay expression. This evaluation is performed by measuring an objective index of force sensor attached to a VR controller and subjective indexes of rating scales and interviews.

3. METHOD

3.1 *Approach*

Figure 1 shows the conceptual diagram of augmented cross-modality system. This system aims not to reproduce the way to interact with objects in real world or stimuli received from the interaction, but to design expressions for VR by translating physiological responses, knowledge and impression about the experience of the interaction in real world into audio-visual stimuli. With these augmented cross-modal expressions, two effects are expected. The first one is synchronization of actual physiological responses with expressions of them and the second one is evoking the knowledge and impression related to the target experience due to the designed expressions. Through this approach, it is expected that though the way to interact with objects or the stimuli received from the interaction is different from the real one, the VR experience resembles the characteristics of real-life experience.

There are two main advantages in the proposed method. The first one is that the proposed method has good compatibility with immersive VR using HMD which has a high degree of freedom of audio and visual expressions. Due to the high degree of freedom of expressions, the possibility of audio-visual expressions in VR expands further than in conventional 2-dimensional display or mixed reality (MR) technology. Thus, it is assumed that it is possible to present haptic information with more variety and wider scalability. The second is that the examination of the design of audio and visual expressions is a main task to do for this method. Therefore, there is an advantage that devices tend to be comparably simple and can be realized with a relatively simple system without limiting the degree of how participants can move freely. In addition, another advantage is that hardware problem such as maximum output of motor, weight, latency and spatial resolution does not occur frequently in the present study.

3.2 *Stimuli*

As the stimulus of the proposed method, physiological responses, knowledge and impression about the experience of a user lifting a heavy object were translated into visual–audio expressions. Specifically, a hand model tremor and a skin color of the hand model turning red (an expression for strong gripping) were presented as visual expressions, and heartbeat getting louder and faster was presented as an audio expression. In addition, these expressions were given in stages over time while a participant was lifting a virtual object in VR. These expressions are added to the condition of delaying the speed at which the virtual object and the hand model follow the actual hand movement (delay expression). Figure 2 shows the behavioral image of the proposed method in time series. The detail of each expression is described below.

In the delay expression, the virtual object (and a hand model) moves to the coordinates which is linearly complemented by the parameter k ($0 \leq k \leq 1, k \in R$) between the virtual object and the VR controller for each frame. Now defining the position of the hand of a participant (same as one of the VR controllers) in the f frame as y_f and the position of the virtual object as Y_f, the expression is as follows.

$$Y_f = Y_{f-1} + (y_f - Y_{f-1}) \cdot k. \tag{1}$$

In this experiment, the delay parameter was purposely set "very slow" ($k = 0.0005$) because of two reasons. One reason is that the objective of the augmented cross-modal expressions is to present a sense of strain of body while lifting a heavy object. Therefore, the "heavy" expression is needed in this case and the delay parameter "0.0005" was confirmed to present a heavy sensation in our preliminary experiment. The other reason is that we wanted to know whether the augmented cross-modal expressions eased the unnaturalness of the large gap between the actual body and virtual body. As we discussed in "A. Problem," the more the delay was, the heavier the weight sense of the participant was. At the same time, however, the individual differences of weight sense were larger and participants felt stronger unnaturalness. The delay parameter "0.0005" is the heaviest parameter in the parameters used in our past study but most participants commented they felt strongest unnaturalness with it. From above, we set the parameter as 0.0005 in the present experiment.

Next, various augmented cross-modal expressions are explained below in time series. First, as the initial condition, heartbeat sound whose volume is around the detection limit at a rate of 0.5 times/sec is presented—namely, participant is less conscious of the heartbeat sound in a normal state though it is noticeable if consciousness is given. Then, lateral vibration whose frequency is 70 rad/sec and amplitude is 1 mm is started as an expression of hand tremor 1 second after a participant lifted up the virtual object. After that, 2 seconds after the start of lifting, the animation starts where the skin color of the hand model turns red as an expression of the strong gripping and it is completed in 2 seconds. The heart rate monotonically increases to 1 time/sec and the heartbeat sound monotonically increases to 5 times the first volume (which is sufficiently loud for being noticeable and is under the allowable limit) within 6 seconds from 4 seconds after the start of lifting to 10 seconds. Each value of these expressions was decided by carrying out user tests in the preliminary experiment. In this experiment, the three conditions below are evaluated.

A virtual object and a hand model follow the user's actual hand

- with completely synchronized (control condition).
- with delay of which the parameter is 0.0005 (delay condition).
- with delay ($k = 0.0005$, same as delay condition) and augmented cross-modal expressions (complex condition).

3.3 *Equipment*

Participants are equipped with HMD for VR and headphones and have a VR controller on the right hand. Force sensors are attached to the trigger and the grip of the VR controller, and the data from these sensors is transmitted to the personal computer (PC) by Bluetooth from the Analog to Digital Converter (ADC) mounted on the waist of the participant. The equipment used in this experiment is as follows.

- HMD for VR: HTC VIVE Headset
- VR controller: HTC VIVE Controller
- Force sensor: Tekscan Flexi Force
- ADC: Plux biosignalsplux ADC

In the VR space, a virtual dumbbell model is placed on a table whose height is 50 cm from the floor. In addition, the local position and rotation of the hand model in VR corresponds to that of VR controller, and it is possible to perform operations such as gripping and releasing virtual objects with triggers of the controller. The experimental system and operation image are shown in Figure 3.

3.4 *Measurements*

Evaluation was carried out by four questionnaires with seven-point scales on the lifting experience of the virtual object, a force sensor and a free description interview. Details are shown below.

Participants are asked to answer the four questionnaires that "Did you feel the weight?", "Did you feel a sense of strong gripping?", "Did you feel that you lifted up the dumbbell?" and "Were you aware of your actual body during the operation?" by 7-point scales from "Strongly agree" to "Strongly disagree." About the questionnaire of whether a participant felt lifting up the dumbbell, participants are taught to judge the reality of the experience of lifting up an object. In addition, about the questionnaires of whether a participant was conscious of themselves during operation,

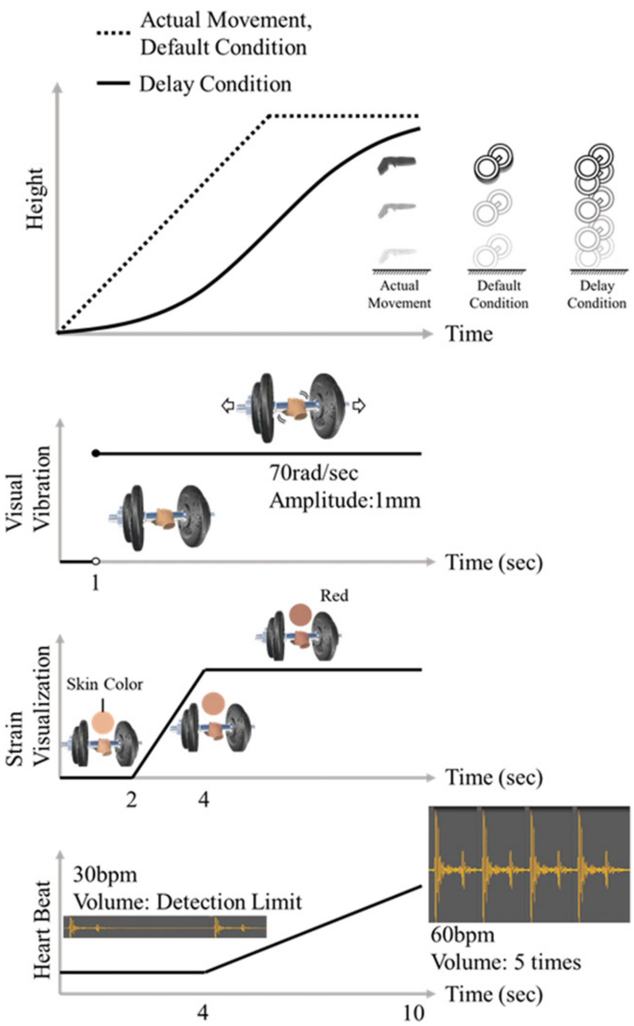

Figure 2. Detailed description of stimuli in time series.

participants were taught to judge whether the position or posture of their actual body were conscious of.

Force sensors are used to measure the strength of gripping the controller while lifting the virtual object as an objective index of illusion intensity and quality of experience. The reason why the force sensor is used is that in our preliminary experiment which evaluated the illusion intensity and the quality of the experience with the force sensor in similar haptic illusion presentation, a certain tendency was found. The force sensor measurement was performed at sampling rate of 1 [kHz] and resolution of 2^16 [bit]. Conversion from the acquired digital value D to force F [kgf] is calculated according to the following equations. Now, 3 [v] of the numerator in the equation (2) is the maximum output voltage of the biosignals Plux ADC, and 6 [v] and 47 [Ω] of the denominator in equation (3) represent the applied voltage and the reference resistance (GND side) respectively when the force sensor Flexi Force is pressured, and 0.000331 [mS / kgf] of the denominator in equation (4) is the rate of change of the force sensor Flexi Force.

$$Vout[V] = \frac{3D}{2^{16}} \tag{2}$$

$$G[mS] = \frac{Vout}{((6 - Vout) \cdot 47)} \tag{3}$$

$$\mathrm{F[kgf]} = \frac{G}{0.000331}. \tag{4}$$

3.5 *Procedure*

The experiment participants were 20 university students in their 20s (18 males, 2 females). They were explained the purpose, method and flow of the experiment beforehand and asked to fill in the consent form and the attribute sheet. Next, they mounted the HMD to see the experimental environment in the VR space, and then were explained the tasks and precautions in detail. After that, in order to familiarize the operation and the environment in the VR space, they operated the dumbbell object of the control condition freely as a practice trial. This practice trial ended when they were able to operate as they wanted and did not feel the sense of incongruity with hand model. After the practice trial, main experiment is carried out in accordance with the following flow.

1. The experimenter randomly selects one condition of the three conditions.
2. With the signal of the experimenter the participant lifts the dumbbell object toward one's chest height.
3. After ten seconds from the start of lifting, the experimenter sends a signal and the participant releases the dumbbell object at the height.
4. The participant removes the HMD and answers to the questionnaires.
5. Repeat steps 1 to 4 for each condition.
6. Set steps 1 to 5 as one set and carry out 4 sets in total.

4. RESULT

For each question item, each result from "Strongly disagree" to "Strongly agree" was corresponded from 1 to 7 points as a rating point. The results of each question item are described in order below.

In the question "Did you feel the weight?", there is a tendency that participants felt heavier with the delay and complex conditions than the control condition, and the dispersion of the evaluation tended to be relatively large particularly in the delay condition. A one-way ANOVA analysis was conducted on the rating points with the conditions as factors and a significant difference was found ($F(2, 237) = 57.19$, $p < 0.001$). Therefore, TukeyHSD test was processed as a subordinate test, and a significant difference was found between both control–delay condition and control–complex condition with $p < 0.001$ (Fig. 4). In the interview, 14 of the 20 participants mentioned the difference in a weight feeling between the delay condition and the complex condition. According to the comments, 7 participants felt heavier with complex condition, 6 felt about the same weight between the conditions and 1 participant felt heavier with delay condition.

In the question "Did you feel a sense of strong gripping?", the feeling of strong gripping tended to increase, followed

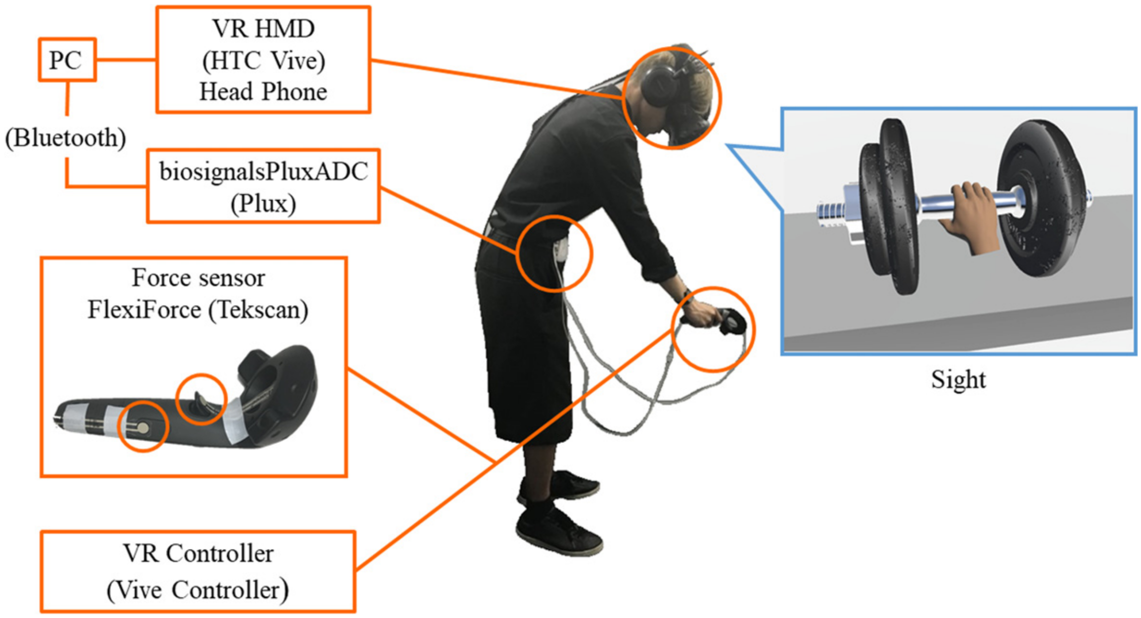

Figure 3. The experiment system.

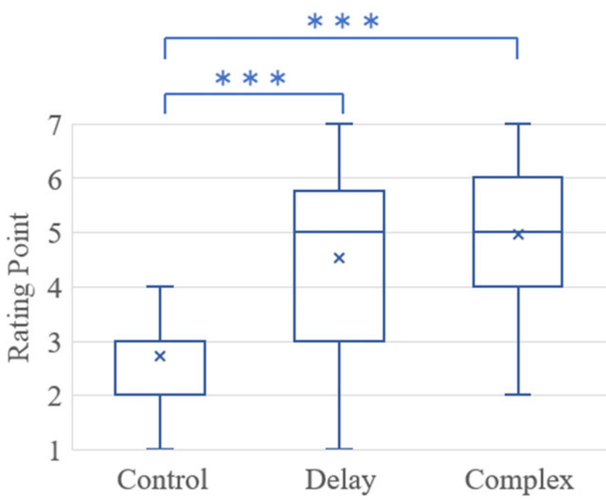

Figure 4. Boxplot of the result of the questionnaire on a sense of weight; boxplots show the median, 25th and 75th percentiles; error bar indicates minima and maxima; cross indicates mean; ***: $p < 0.001$, ** $p < 0.01$, *: $p < 0.05$, •: $p < 0.1$.

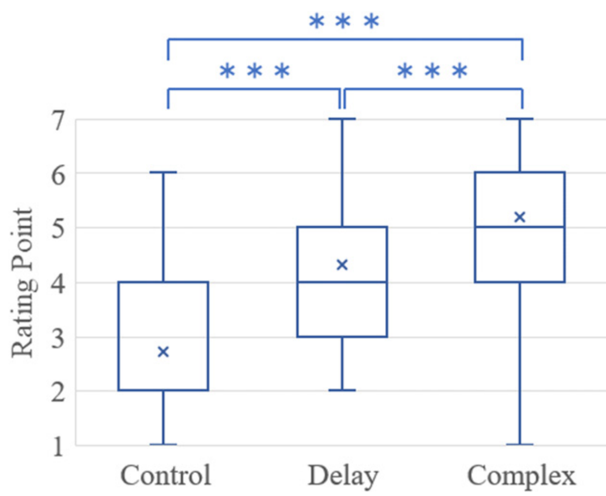

Figure 5. Boxplot of the result of the questionnaire on a sense of strain; boxplots show the median, 25th and 75th percentiles; error bar indicates minima and maxima; cross indicates mean; ***: $p < 0.001$, ** $p < 0.01$, *: $p < 0.05$, •: $p < 0.1$.

in order by control, delay and complex conditions. Similarly, a one-way ANOVA analysis was conducted with conditions as a factor, and a significant difference was observed (F (2,237) = 59.48, $p < 0.001$). Thus, a TukeyHSD test was processed as a subordinate test and as a result, a significant difference was found with $p < 0.001$ among all pairs of the conditions (Fig. 5). In the interview, many participants commented on the influence on the sense of strong gripping especially under the complex condition and 17 of the 20 participants commented on the relationship between a sense of strong gripping and augmented cross-modal expressions. 15 of the 17 participants responded that the sense of strong gripping was enhanced by the expressions and in particular 2 participants commented on hand tremor, 1 participant on heartbeat, 2 participants on both the change of skin color and hand tremor and 10 participants on entire augmented cross-modal expressions.

In the question "Did you feel that you lifted the dumbbell?", The rating point tended to be the highest in the control condition and be relatively higher in the complex condition compared with the delay condition. Analyzed in the same way, a significant difference was found by analysis of variance (F (2, 237) = 19.12, $p < 0.001$), and a significant difference was found with $p < 0.001$ between both control–delay condition and control–complex condition by TukeyHSD test (Fig. 6). In the interview, most of the participants commented that they felt the act

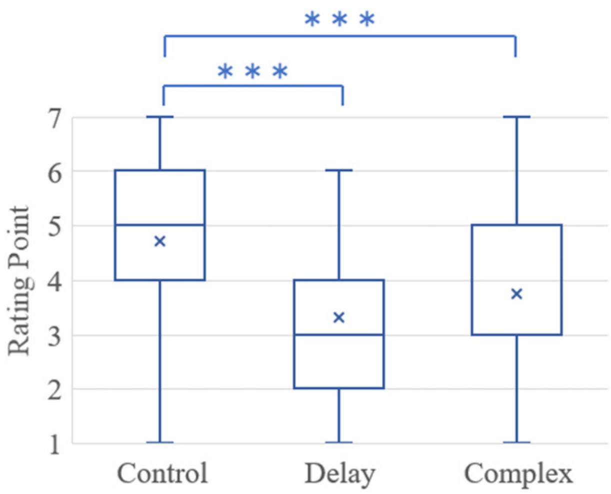

Figure 6. Boxplot of the result of the questionnaire on a sense of lifting a dumbbell; boxplots show the median, 25th and 75th percentiles; error bar indicates minima and maxima; cross indicates mean; ***: $p < 0.001$, ** $p < 0.01$, *: $p < 0.05$, •: $p < 0.1$.

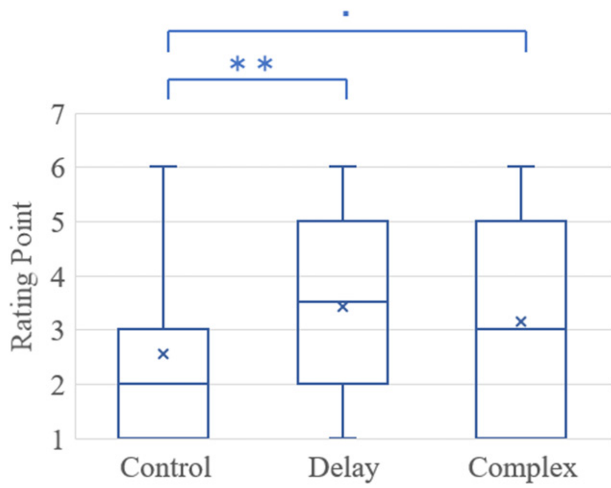

Figure 7. Boxplot of the result of the questionnaire on consciousness of actual body; boxplots show the median, 25th and 75th percentiles; error bar indicates minima and maxima; cross indicates mean; ***: $p < 0.001$, ** $p < 0.01$, *: $p < 0.05$, •: $p < 0.1$.

of lifting was real because the dumbbell object and hand model completely followed the movement of their body and they could move them as desired in the control condition. In addition, as comments on the delayed expression, 6 participants commented that the sense of lifting and reality were lost because they felt a sense of incompatibility on the situation that the dumbbell object and hand model did not follow immediately and they could not move them as they desired. Furthermore, 5 participants commented that they felt the sense of manipulating or pulling something rather than lifting. On the other hand, as comments on the complex condition, 7 participants commented that they felt they were actually lifting a dumbbell by the augmented cross-modal expressions or the expressions match the experience of lifting a heavy object. In addition, 2 participants commented that they felt something that is not a part of their body is moving.

In the question 'Were you aware of your actual body during the operation?', the rating point tended to be high in delay condition and complex condition. Analyzed in the same way, a significant difference was observed by analysis of variance (F (2,237) = 4.96, $p < 0.01$), and as a result of TukeyHSD test, a significant difference was found with $p < 0.01$ between control–delay condition and a significant trend with $p < 0.1$ between control–complex condition (Fig. 7). In the interview, 9 participants commented that they felt discomfort due to the awareness of the separation or gap between the actual body and the hand model by the delay expression. Additionally, there were comments on the augmented cross-modal expressions that their actual body is being conscious of due to the awareness of the difference between their actual heartbeat and the presented heartbeat, or that there was a feeling that the hand model is not a part of their own body due to expressions. On the other hand, also there were positive comments on the expressions that a sense of immersion to the contents increased, participants were less conscious of the gap and so they did not feel discomfort due to the gap.

About the force sensor data, there was a tendency to grip the controller more strongly, followed in order by the control condition, the delay condition and the complex condition. Furthermore, especially under the complex condition, it seems that participants grabbed not only the trigger part but also the whole hand. Because data of two participants were partially missing due to communication failure between ADC and PC, the statistical processing was carried out with data of 18 people whose all data were accurately acquired. As a processing of raw data, the digital data was converted to force (kgf) by Eqs. (2)–(4) and the average value for 10 seconds during proceeding lifting task was calculated for each trial. Analysis of variance was similarly conducted in each of the trigger part and the grip part. As a result, a significant difference was found in the trigger part (F (2,230) = 8.34, $p < 0.001$) and in the grip part (F (2,230) = 3.21, $p < 0.05$). Thus, TukeyHSD test was processed and as a result, a significant difference was found between both the control–delay condition and the control–complex condition in the trigger part with $p < 0.01$ (Fig. 8) and between the control–complex condition in the grip part with $p < 0.05$ (Fig. 9).

As other comments of interviews, there was a comment that the enjoyment and the reality are improved or there was a feeling that the sense on actual body is changed by augmented cross-modal expressions.

5. DISCUSSION

First of all, with regard to weight sensation, it was confirmed that the sense of weight was significantly increased through the delayed expression by the result of the rating scales, and from the comments, the tendency is observed that the sense of weight is further increased by the augmented cross-modal expressions. In addition, in this experiment, the

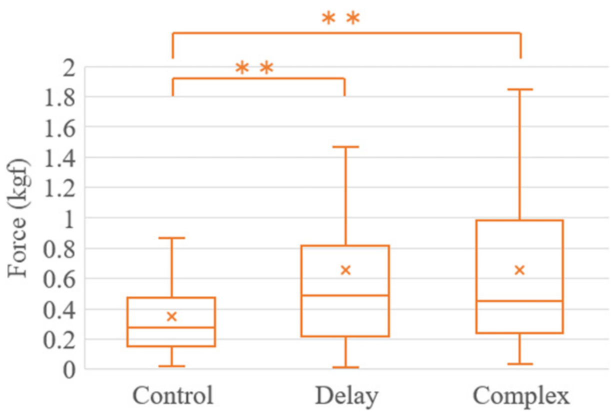

Figure 8. Boxplot of the result of the force sensor of trigger part; boxplots show the median, 25th and 75th percentiles; error bar indicates minima and maxima; cross indicates mean; ***: $p < 0.001$, ** $p < 0.01$, *: $p < 0.05$, •: $p < 0.1$.

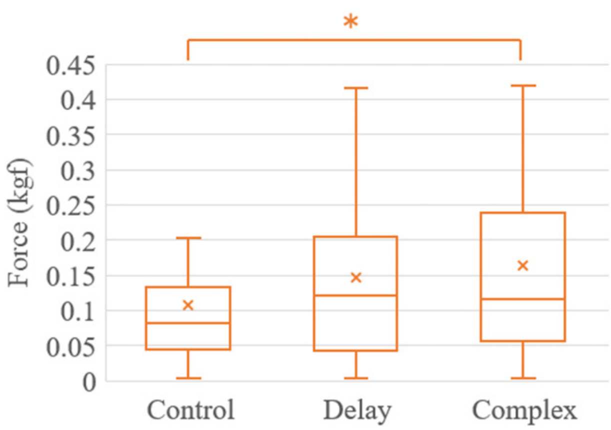

Figure 9. Boxplot of the result of the force sensor of grip part; boxplots show the median, 25th and 75th percentiles; error bar indicates minima and maxima; cross indicates mean; ***: $p < 0.001$, ** $p < 0.01$, *: $p < 0.05$, •: $p < 0.1$.

degree of delay was large and individual differences were observed in the occurrence of weight sensation by delay expression. Moreover, there were participants who hardly felt the weight sense. These individual differences with large delay expression were also observed in our preliminary experiment. However, from the comments, the individual differences tended to be eased by augmented cross-modal expressions.

As one of the factors of the individual differences with the delay expression, it is considered that due to the expression in which the positions or behaviors of the actual body and the virtual body are extremely separated, some participants were strongly conscious of the separation. Participants said, “Feeling of something coming along with my movement,” “Feeling just slow against my movement” or “A sense of ownership to the hand model disappears” with regard to the incompatibility on the delay expression. In addition, it can be also one of the factors that the delay expressions were understood in different contexts from the sense of weight or lifting, such as a sense of slow, pulling or manipulating an object.

On the other hand, the reason why individual differences or incompatibility with the delay expression tended to be eased in the complex condition was considered as follows. The augmented cross-modal expressions increased the participants’ sense of immersion and concentration in the content, and it is assumed that the sense of separation between the virtual and real body was relatively unconscious. In addition, participants commented that they felt the augmented cross-modal expressions matched the experience of lifting a heavy object and the haptic experience was real. Therefore, it is considered that the experience in VR got closer to the experience of lifting a heavy object with the augmented cross-modal expressions than only with delay expressions.

This tendency is also found in the result of the rating scales of “Were you aware of your actual body during the operation?”. However, there were some participants who felt uncomfortable in the augmented cross-modal expressions and not all participants were able to feel the sense of weight even under the complex condition. Therefore, further consideration is necessary for expressions in order to present weight sense to all users in common.

In addition, with regard to the force of hand and a sense of strong gripping under the experience, the questionnaire of rating scales resulted in a significantly higher score, followed in the order by the control, the delay and the complex condition (Fig. 5). The trend can be seen also in the objective index. The value of force sensor of trigger part is significantly larger in delay and complex conditions than control condition, and that of grip part is significantly larger in complex condition than in control condition (figures 8, 9). Particularly with regard to the augmented cross-modal expressions, there are the comments that most participants feel an enhancement of a sense of strong gripping by the expressions, and at the same time, the comments that “Fun,” “Reality is improved,” “Feeling like a hand getting hot” or “Get a feeling of tension.” Therefore, it was suggested that the quality of experiences was changed and enhanced by the augmented cross-modal expressions. Furthermore, it was also considered that the augmented cross-modality has a physical or behavioral influence such as the way to grip and the strength of gripping because the value of the force sensor of the grip part was significantly high in the complex condition.

6. CONCLUSION

In this paper, we proposed a method of enhancing and changing the quality of total haptic experiences as intended in a VR space by translating physiological responses, knowledge and impressions related to the targeted experience into audio-visual expressions, as a method of presenting cross-modal haptic illusion. The conventional pseudo-haptic method of generating a sense of weight uses delay expression while a user is lifting a virtual object. In addition to that, our method presented the expressions such as “Visual hand trembling," "Skin color of a hand model turning red" and "Increasing of the heart rate and the volume of heartbeat" as augmented cross-modal expressions. This method was evaluated by the experiment of comparing the condition using only delay expression (delay condition), the condition using delay expression with the augmented cross-modal expressions (complex condition) and the condition without these expressions (control condition).

Based on the results of the experiment, it is confirmed that due to the augmented cross-modal expressions of strain, most participants experienced an enhancement of the sense of strong gripping. In addition, several participants commented that this enhancement leads to change the quality of participants' total haptic experiences in VR and makes it closer to the experience of lifting a heavy object more than only delay. Furthermore, due to the result that the expression of strain increased the gripping force, it is suggested that the actual physiological responses and behavior could be induced by augmented cross-modal expressions.

We consider that the effectiveness of the proposed method was confirmed at a certain level. In the future, we will explore other augmented cross-modal expressions presenting haptic experiences other than weight sense with large scalability in VR.

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REFERENCES

[1] M. A. Srinivasan and C. Basdogan, "Haptics in virtual environments: taxonomy, research status, and challenges," Comput. Graph. **21**, 393–404 (1997).

[2] T. H. Massie and J. K. Salisbury, "PHANToM haptic interface: a device for probing virtual objects," *Proc. ASME Winter Annual Meeting Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (American Society of Mechanical Engineers, New York, NY, 1994), 55-1, pp. 295–299.

[3] M. Sato, "SPIDAR and virtual reality," *Proc. 5th Biannual World Automation Congress* (IEEE, Piscataway, NJ, 2002), pp. 17–23.

[4] CyberGlove Systems Inc., 'CyberGrasp', http://www.cyberglovesystems.com/cybergrasp (accessed 2018).

[5] S. Nagawara, H. Kajimoto, N. Kawakami, S. Tachi, and I. Kawabuchi, "An encounter-type multi fingered master hand using circuitous joints," *Proc. IEEE Int'l. Conf. on Robotics and Automation* (IEEE, Piscataway, NJ, 2005), pp. 2667–2672.

[6] A. Lécuyer, "Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback," Presence: Teleoperators and Virtual Environments **18**, 39–53 (2009).

[7] Y. Taira, Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose, "Controlling fatigue while lifting objects using Pseudo-haptics in a mixed reality space," *2014 IEEE Haptics (HAPTICS)* (IEEE, Piscataway, NJ, 2014), pp. 175–180.

[8] M. Rietzler, F. Geiselhart, J. Gugenheimer, and E. Rukzio, "Breaking the tracking: enabling weight perception using perceivable tracking offsets," *Proc. 2018 CHI Conf. on Human Factors in Computing Systems* (ACM, New York, NY, 2018).

[9] M. Rietzler, F. Geiselhart, J. Frommel, and E. Rukzio, "Conveying the perception of kinesthetic feedback in virtual reality using state-of-the-art hardware," *Proc. 2018 CHI Conf. on Human Factors in Computing Systems* (ACM, New York, NY, 2018).

[10] P. Issartel, F. Gueniat, S. Coquillart, and M. Ammi, "Perceiving mass in mixed reality through pseudo-haptic rendering of Newton's third law," *IEEE Virtual Reality Conf., VR 2015 – Proceedings* (IEEE, Piscataway, NJ, 2015), pp. 41–46.

[11] S. Hashiguchi, Y. Sano, F. Shibata, and A. Kimura, "R-V Dynamics illusion: psychophysical influence on sense of weight by mixed-reality visual stimulation of moving objects," *VAMR 2014: Virtual, Augmented and Mixed Reality, Designing and Developing Virtual and Augmented Environments* (Springer, Cham, New York, NY, 2014), pp. 55–64.

[12] A. Takahashi, K. Tanabe, and H. Kajimoto, "Relationship between force sensation and stimulationparameters in tendon electrical stimulation," *AsiaHaptics'16* (Springer, Singapore, 2016).

[13] K. Tanabe, S. Takei, and H. Kajimoto, "The whole hand haptic glove using numerous linear resonant actuators," *IEEE World Haptics Conference 2015* (IEEE, Piscataway, NJ, 2015).

[14] M. Azmandian, M. Hancock, H. Benko, E. Ofek, and A. D. Wilson, "Haptic retargeting: dynamic repurposing of passive haptics for enhanced virtual reality," *Proc. 2016 CHI Conf. on Human Factors in Computing Systems* (ACM, New York, NY, 2016), pp. 1968–1979.

[15] K. Matsumoto, Y. Ban, T. Narumi, Y. Ynase, T. Tanikawa, and M. Hirose, "Unlimited corridor: redirected walking techniques using visuo haptic interaction," *ACM SIGGRAPH 2016 Emerging Technologies* (ACM, New York, NY, 2016).

[16] R. Nagao, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose, "Ascending and descending in virtual reality: simple and safe system using passive haptics," IEEE Trans. Vis. Comput. Graphics **24**, 1584–1593 (2018).

[17] C. M. Davis and W. Roberts, "Lifting movements in the size-weight illusion," Attention Perception & Psychophysics **20**, 33–36 (1976).

[18] G. Buckingham, N. S. Ranger, and M. A. Goodale, "The material-weight illusion induced by expectations alone," Attention Perception & Psychophysics **73**, 36–41 (2011).

[19] R. R. Ellis and S. J. Lederman, "The golf-ball illusion; evidence for top-down processing in weight perception," Perception-London **27**, 193–303 (1998).