The effects of changing the mental model of one's body and sense of body ownership on pain perception

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Abstract

The mental model of one's body plays an important role in determining subsequent actions. We changed the mental model using visual information and observed the effects of such change on pain perception. These effects were compared to the effects of changes in the sense of body ownership, which is the sensation that something is a part of one's own body. Some researchers have shown that the sense of ownership is a factor modulating pain perception. In our experiments, we manipulated the visibility of participants' limbs using Mixed Reality (MR) techniques and measured their perceived pain and feelings while observing their limbs. Results showed the sensation that nothing can touch one's limbs decreased the strength of perceived pain.

Keywords: Sense of ownership, body representation, pain perception, multimodality, mixed reality

Introduction

We determine our next actions based on our own body representation or mental model of our bodies (Barsalou, 2008; Warren, 1984). Some features, such as posture, muscular strength, and size, change every moment or as we grow. Other basic features, such as bone structure, nerve mechanisms, and material properties, remain almost constant through life. If we can modulate such basic features in our mental model, can our perceptions be changed by the model? In this study, we investigate the relationship between the mental model of one's own body and perception, focusing on pain perception.

Sense of Ownership

One of the important sensations affecting the perception of pain is the sense of ownership or physical possession of one's body parts, such as hands and legs. The perception of ownership can be easily extended to non-body parts. The most famous example is the rubber hand illusion (Botvinick & Cohen, 1998): When a rubber hand and a participant's hand are repeatedly touched simultaneously while the participant is watching the rubber hand, he/she feels as if the rubber hand were his/her own.

Obviously, we cannot feel pain if something other than one's own body is attacked. Consistent with this idea, some researchers have shown that the pain threshold increases as the sense of ownership decreases (Martini, Kilteni, Maselli, & Sanchez-Vives, 2015; Martini, Pérez-Marcos, & Sanchez-Vives, 2014; Pamment & Aspell, 2017; Zanini, Montalti, Caola, Leadbetter, & Martini, 2017). However, some have argued that the sense of ownership has no effect on pain perception (Mohan et al., 2012).

Mental Model of Own Body

We propose that another important factor affecting the perception of pain is the material property of skin in a mental model of own body. If you imagine your skin is made with iron, for instance, you may not feel pain if someone hit you. Senna, Maravita, Bolognini, and Parise (2014) introduced the marble hand illusion: Participants in their study heard the sound of marble being struck when a hammer touched their hand. After five minutes, they felt their hands becoming stiffer, heavier, harder, less sensitive, and unnatural. However, Senna et al. (2014) did not investigate whether the manipulation affected the level of pain perception.

Another study showed that just changing the color of the skin was enough to change the threshold for heat pain; however, the effect of the manipulation on the mental model was not investigated (Martini, Pérez-Marcos, & Sanchez-Vives, 2013). These studies suggest the possibility that the mental model of one's body can be modulated to affect pain perception.

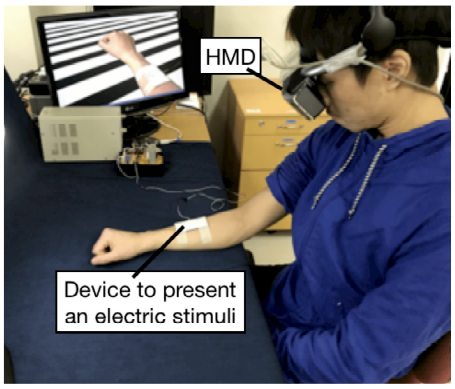
Aim of This Study

As previously noted, many previous studies have suggested that a sense of ownership was an important factor in pain perception. However, there is a possibility that the mental model of one's body is also modulated by manipulating ownership. Therefore, it is not clear whether pain perception is really related to the sense of ownership. To clarify the top-down effect on pain perception, we need to identify which of the mental model of the body or the sense of ownership has a stronger effect.

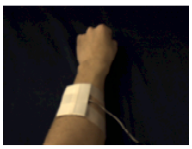
Mixed Reality

In previous studies, most researchers used a rubber hand or virtual body to manipulate participants' ownership or mental model of the body. Before introducing these manipulations, researchers had to increase participants' perception of ownership of these materials. For example, in Martini et al. (2015)'s experiment, participants viewed a virtual environment and virtual body from a first-person perspective for one minute. Afterward, the transparency of the virtual body was increased to decrease the sense of ownership. They showed that a low sense of ownership decreased pain sensitivity.

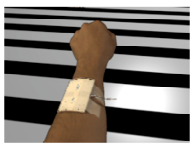
To be accurate, what the participants observed was not their actual body part but a rubber or virtual hand. Even if researchers made a realistic-looking hand, it would not be



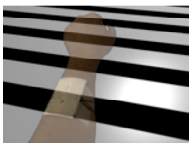
(a) Experimental set-up



(b) View from the camera



(c) Hand and virtual background



(d) Opacity 50%

Figure 1: Experimental environment and the manipulation of the limb.

a real hand; discrepancies between it and their body might give the participants an uncomfortable feeling. We would not be able to determine whether participants' mental models of their bodies changed or if they constructed new mental models for the fake hand. Additionally, while the manipulations were performed on the fake hand, stimuli were administered to the real hand.

To overcome the limitations of the fake hand, we introduce a Mixed Reality (MR) technique, which allowed us to change the properties of objects in the real environment or add virtual objects to the real environment (Kannape, Smith, Moseley, Roy, & Lenggenhager, 2019). With this technique, we made participants' own limbs appear transparent and observed the change in their perceptions of ownership, mental models of their bodies, and pain perception.

Apparatus

MR Environment

Figure 1 shows the experimental environment. We adopted a video see-through-type HMD (Canon, HM-A1) and MR platform system (Canon, MP-110). We acquired the participant's perspective from the camera on the HMD and manipulated the alpha value for the area of the participant's hand as shown in Figure 1. Five levels of the alpha value were used: 100% (fully visible), 75% visibility, 50% visibility, 25% visibility, and 1% visibility (almost invisible). A background image under the participant's hand had a black-and-white stripe to facilitate the perception of transparency.

Electric Stimulus

The pain presentation device was a boosted current using a Cockcroft-Walton circuit as an electric stimulus generation apparatus through an input/output board (Kyohritsu Electronic Industry Co., Ltd., RBIO - 2 U). A conductor (diameter: 0.12 mm, 10 cores) was fixed to a 1 mm-thick rubber sheet. We presented the pain sensation by applying a current to this conductor. The intensity of electrical stimulation was 320 V at a current of 1.8 mA, and the pulse width was 0.15 s.

Experiment 1

The level of ownership and mental model of their limbs were recorded at each level of opacity from 100% (fully visible) to 1% (almost invisible). We added a blackout (BO) condition in which no visual stimulus was presented.

Method

Participants Fourteen students participated in Experiment 1.

Measurement The participants assessed their levels of pain using a visual analog scale (VAS). We prepared a 100-mm line whose left end indicated "no pain" and whose right side indicated "worst possible pain." The participants were asked to draw a cross on the point reflecting the level of pain they perceived.

We developed a questionnaire to assess the mental model. It consisted of 20 items including feelings thought to be important for pain perception. The order of the items was randomized.

Procedure The experiment consisted of two successive blocks: the questionnaire and a pain perception block. All participants started with the questionnaire and then continued to the pain perception block. Before starting the experiment, the participants were asked to read and sign a consent form.

Questionnaire Block After receiving brief instructions, the participants sat at a desk and rested an arm on the desk as illustrated in Figure 1(a). They donned the HMD and saw their non-manipulated limb through a camera (Figure 1(c)) before watching their limb becoming transparent. At the end of the transformation, they watched their transformed limb (e.g., Figure 1(d)) for 10 seconds. Next, they removed the HMD and completed the questionnaire, which employed a 7-point Likert scale. All participants completed each opacity condition in random order except for the BO condition, in which their limb was completely invisible.

Pain Perception Block The procedure was identical to the questionnaire block until the participant observed their transformed limb. In the pain perception block, they were given an electric stimulus following a cue from the experimenter while they were watching their transformed limb. After the stimulus was given, they removed the HMD and assessed the strength of the pain they perceived. The opacity conditions were presented to participants in random order. In both blocks, two minutes rest was provided between each condition.

Table 1: Result of factorial analysis.

Item	Factor loading				
	Ownership[1]	Transparency	Intangibility	Anxiety[2]	Weakness
I feel as if the observed arm is my own arm	-0.932	-0.167	-0.061	0.166	0.033
The observed arm doesn't look mine	0.80	0.202	-0.057	-0.132	-0.129
I feel as if the observed arm is not my own arm	0.736	-0.020	0.422	-0.115	-0.009
My arm seems to be not present in the environment	0.733	0.220	0.323	-0.172	-0.049
I feel the observed arm is a real one	-0.723	-0.310	-0.130	0.204	-0.093
I feel as if my arm is transparent	0.244	0.932	0.237	-0.072	0.067
The arm is transparent	0.174	0.861	0.226	-0.094	0.105
My arm feels sparse	0.338	0.739	0.339	-0.008	0.112
I feel as if something can pass through my arm	0.090	0.436	0.834	-0.025	-0.055
I feel as if my arm is empty	0.137	0.304	0.832	0.008	-0.032
I feel as if I am a ghost	0.220	0.188	0.610	-0.137	-0.278
My arm feels numb	0.322	0.045	0.517	-0.434	-0.272
I don't feel fear by observing the arm	-0.069	-0.164	-0.086	0.883	0.161
I feel ill by observing the arm	0.122	0.021	0.087	-0.804	-0.118
I feel relieved by observing the arm	-0.250	-0.169	-0.249	0.735	0.234
I feel calm by observing the arm	-0.185	0.122	0.189	0.390	-0.054
My arm feels softer	0.062	0.056	-0.095	0.064	0.900
My arm feels weakened	0.126	0.115	-0.110	0.055	0.800
My arm feels lighter	-0.209	-0.023	0.053	0.093	0.509
My arm feels insensitive	-0.058	0.102	-0.264	0.232	0.480

[1] These loadings mean the contribution to "less ownership." Score of this factor was reversed to make easy to understand the results.
[2] These loadings mean the contribution to "less anxiety." Score of this factor was reversed to make easy to understand the results.

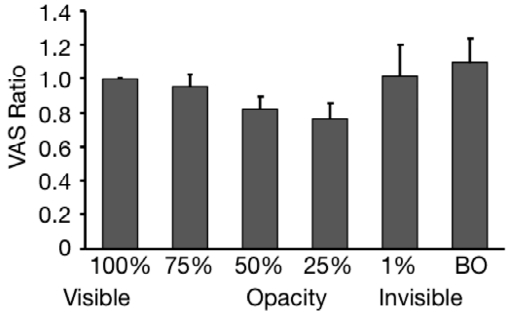


Figure 2: Means of pain assessment in Experiment 1.

Results and Discussion

Pain Perception We measured the distance from the left-most point to the marked point on the pain scale. The length in the 100% condition was the criterion value, and the length in each condition was converted to its ratio to the criterion value (Figure 2). One participant whose ratio deviated over 3 SD from the average was excluded from the following analyses. A repeated ANOVA showed the effect of opacity was significant ($F(5,60) = 2.467, p = .042$). In the 25% condition, the perceived strength of pain was lower than in the fully visible (100%) condition ($p = .036$). Perceived pain was stronger in the 1% and BO conditions than in the 50% and 25% conditions (ps $< .050$).

These findings and the tendencies in Figure 2 show that as the limb became more transparent, the level of perceived pain became weaker. However, when the limb was nearly or completely invisible, the strength of pain rose to near the value of the fully visible condition.

Questionnaire and Pain Perception We conducted a factorial analysis using the ratings of the questionnaire. We found five factors shown in Table 1: ownership, transparency, intangibility (i.e., nothing can touch their limb), anxiety, and weakness. The bigger value means the strong feeling for the factor.

A repeated ANOVA for each factor score (Figure 3) shows opacity value has a significant effect on all factors other than weakness (ownership $F(12,48) = 23.182, p < .001$; transparency $F(12,48) = 64.927, p < .001$; Intangibility $F(12,48) = 25.86, p < .001$; anxiety $F(12,48) = 6.716, p < .001$). For the ownership score, there was a significant difference in all pairs other than the pair of 1% and 25% and the pair of 50% and 75% (ps $< .05$). For the transparency score, the score in the 100% condition was higher than for any other conditions (ps $< .001$). For the intangibility score, the differences in scores between the 100% condition and all other conditions and between the 25% and 75% conditions were significant (ps $< .005$). For the anxiety score, the score in the 100% was bigger than that in all other conditions except for the 75% condition (ps $< .01$).

Table 2 shows the correlation coefficient values for the scores of all pairs among five factors and pain perception. We excluded the 1% condition from this analysis because

Table 2: Coefficient values in Experiment 1.

	Ownership	Transparency	Intangibility	Anxiety	Weakness
Ownership					
Transparency	-0.528 ****				
Intangibility	-0.467 ****	0.634 ****			
Anxiety	-0.471 ****	0.166	0.377 **		
Weakness	0.090	0.124	-0.295 *	-0.274 *	
Pain	0.195	-0.357 **	-0.305 *	-0.183	0.072

$^{+}p < .01$, * $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

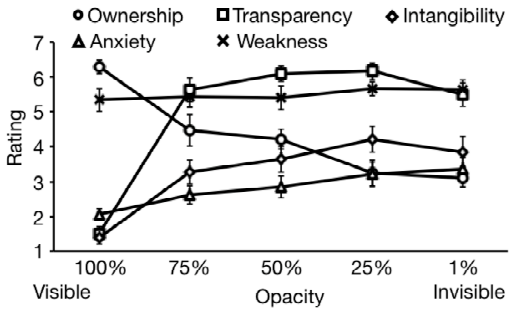


Figure 3: Mean scores for each factor in each condition.

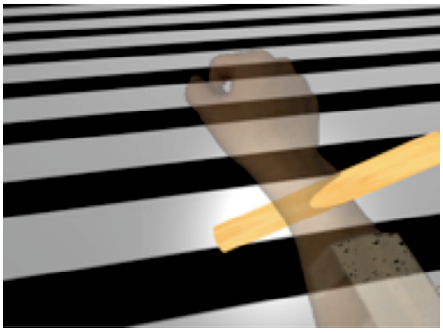


Figure 4: Manipulation in the PT condition: The virtual stick passing through the limb.

some participants shared that they could not see their limbs in this condition, which had a different effect on pain perception than seeing the transparent limb.

The results of correlation analysis show a negative correlation between the level of pain and the scores of transparency and intangibility. Sense of ownership did not correlate to the strength of pain, contrary to the results of the previous studies. In Experiment 2, to identify the most crucial factor for pain perception, we added manipulations changing the perceptions of ownership and intangibility.

Experiment 2

Two manipulations were introduced in Experiment 2. One was "passing through (PT)," in which we passed a virtual stick through the participant's limb as shown in Figure 4. The PT manipulation would increase the sensation of intangibility. Another was "spontaneous movement (SM)," in which the participant moved his/her finger. Many studies showed that observing the body moving in the way as they wanted to increase the sense of ownership. The experiment was a 2 (opacity: 25% and 100%) $\times$ 2 (PT manipulation: PT and no-PT) $\times$ 2 (SM manipulation: SM and no-SM) within-participants design.

Method

Participants Eleven students participated in Experiment 2.

Procedure The procedure was identical to that used in Experiment 1, except that we added the PT and SM manipulations in some conditions. In the PT condition, we moved the virtual stick 10 times as it passed through the participant's limb (Figure 4). In the no-PT condition, we added no manipulation, changing the feeling of intangibility. For the SM manipulation, the participant bent his/her finger as instructed by the experimenter. In the no-SM condition, the participant was told nothing and did not move his/her finger or limb. The manipulation(s) were added before the participant answered the questionnaire and before the electric stimuli were given. The PT manipulation was always conducted before the SM manipulation.

Results and Discussion

Manipulation Check One participant who hardly felt pain in any condition was excluded from the following analyses. At first, we calculated the scores for the five factors found in Experiment 1 to confirm the effects of the manipulations. We conducted a 2 (opacity: 25% and 100%) $\times$ 2 (PT manipulation: PT and no-PT) $\times$ 2 (SM manipulation: SM and no-SM) ANOVA on the scores for ownership and intangibility feelings. The ANOVA for ownership feelings showed that SM manipulation had no effect. The only significant effects were the main effect of the opacity factor ($F(1,9) = 26.396, p < .001$) and the interaction between the opacity and PT manipulation factors ($F(1,9) = 11.505, p = .008$). The score for ownership feeling was generally higher when the limb was fully visible. The PT manipulation decreased the ownership in the 100% condition ($F(1,18) = 9.172, p = .007$). The SM manipulation had no effect on the score of ownership feeling.

On the other hand, PT manipulation efficiently increased the sensation of intangibility. The main effects of the opacity factor ($F(1,9) = 40.490, p < .001$) and the PT manipulation factor ($F(1,9) = 23.802, p < .001$) were significant

Table 3: Coefficient values in Experiment 2.

	Ownership	Transparency	Intangibility	Anxiety	Weakness
Ownership					
Transparency	-0.702 ****				
Intangibility	-0.533 ****	0.670 ****			
Anxiety	-0.540 ****	0.285 *	0.587 ****		
Weakness	0.039	0.140	-0.226 *	-0.394 ****	
Pain	0.218 $^{+}$	-0.363 ****	-0.405 ****	-0.325 ***	0.167

$^{+}p < .01$, * $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

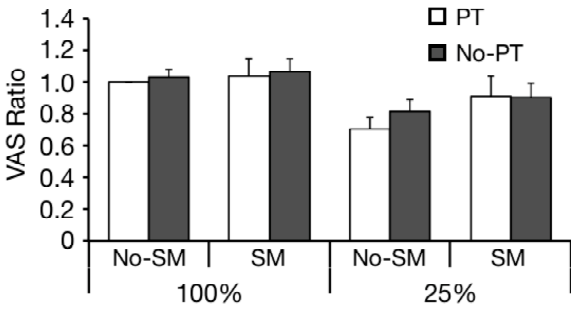


Figure 5: Means of pain assessment in Experiment 2.

for the intangibility score. The interaction between the opacity and PT manipulation factors was also significant ($F(1,9) = 12.091, p = .007$). The effect of PT manipulation was (marginally) significant in both the 25% and 100% conditions (25% $F(1,18) = 4.069, p = .059$; 100% $F(1,18) = 35.888, p < .001$). Although the effect was weak in the 25% condition, the PT manipulation was successful overall.

Pain Perception The VAS rating was converted into the ratio to the length in the 100% condition without either manipulation. Figure 5 shows the mean ratio in each condition. A 2 (opacity: 25% and 100%) $\times$ 2 (PT manipulation: PT and no-PT) $\times$ 2 (SM manipulation: SM and no-SM) ANOVA revealed a significant main effect of the opacity factor ($F(1,9) = 15.244, p = .004$). The interaction between the opacity and SM manipulation factors was marginally significant ($F(1,9) = 3.391, p = .099$). Consistent with the results of Experiment 1, the strength of perceived pain decreased when the participant's limb was transparent. However, the MT manipulation, whose effect was confirmed, had no effect on pain perception.

The Five Factors and Pain Perception The correlation coefficient values among the five factors and pain perception are shown in Table 3. Four factors (ownership, transparency, intangibility, and anxiety) had a (marginally) significant correlation with pain perception, while only ownership and intangibility were related to pain perception in Experiment 1. Many pairs of the scores among the five factors have a strong correlation. Thus, those strong correlations may have caused some spurious correlations.

Table 4: Explanatory powers of factors.

	Explanatory	Coefficient	t value	r^2
Single	Ownership	0.040	1.969^{+}	0.047
	Transparency	-0.042	3.444****	0.132
	Intangibility	-0.072	3.908****	0.164
	Anxiety	-0.096	3.034***	0.094
	Weakness	0.040	1.491	0.015
Multiple	Ownership	-0.013	0.494	0.135
	Transparency	-0.048	2.789**	
	Ownership	< 0.001	0.021	0.164
	Intangibility	-0.071	3.274**	
	Ownership	0.011	0.469	0.108
	Anxiety	-0.087	2.290*	
	Transparency	-0.019	1.203	0.179
	Intangibility	-0.052	2.104*	
	Transparency	-0.034	2.747**	0.185
	Anxiety	-0.072	2.247*	
	Intangibility	-0.058	2.554*	0.175
	Anxiety	-0.040	1.043	

$^{+}p < .01$, * $p < .05$, ** $p < .01$, *** $p < .005$, **** $p < .001$

We tried to identify the crucial factor for pain perception using regression analysis. The results of all analyses are summarized in Table 4. From the results of simple linear regression analyses, four factors (ownership, transparency, intangibility, and anxiety) could explain the strength of perceived pain. We then conducted multiple regression analyses in which each pair of these four factors was chosen as an explanatory variable, and the strength of perceived pain was a dependent variable. When the intangibility score was paired with other factors' score, intangibility was always the only factor with significant explanatory power, and the paired variables' power was not significant. These results suggest that the sensation of intangibility was the crucial factor directly affecting pain perception.

However, the relationship between other factors and the intangibility feeling cannot be determined from this experiment. Further studies are needed to identify whether the other factors explain the intangibility score or whether the intangibility score explains the scores of other factors. Additionally, the r^2 values in our regression analyze were not sufficiently high. Collecting more data will confirm the results of this study.

General Discussion

We investigated the relationships among the mental model of one's own body and pain perception. The crucial factor affecting pain perception was the sensation that nothing can touch one's limbs (intangibility); as this sensation increased, the perceived level of pain decreased. The sense of ownership could not account for the level of perceived pain.

The properties of the mental model of one's body were easily modulated by visual information. A decrease in the perceived opacity of one's body parts decreased feelings of ownership and increased feelings of transparency, intangibility, and anxiety. The passing through manipulation successfully increased the feeling of intangibility. However, observing spontaneous actions did not increase ownership, contrary to findings in previous studies.

Sense of Ownership

We introduced a novel technique, MR, to manipulate body properties. The MR technique can change participant perceptions of the properties of their own limbs. The observed limb had features identical to their own limb and perfectly mimicked its movement. The participants were able to see every movement of their whole limb even if it was a very small movement such as breathing. This phenomenon had already been used to evaluate the sense of ownership; therefore, the additional spontaneous movement had no effect on the feeling of ownership. In future research, we will be able to use other kinds of manipulation, such as a delayed presentation of action, which was found by Kannape et al. (2019) to decrease the feeling of ownership.

In previous studies, the presented rubber or virtual limb was not the participants' own limb. Therefore, the participants created a new mental model of the presented limb and provided the body ownership to it. Changes to the presented limb took the ownership away from it. In short, the participants did not perceive the presented artificial limb to be their own anymore. For this reason, the feeling of ownership had a strong effect on pain perception (e.g., Martini et al., 2014; Pamment & Aspell, 2017); the participants who left more ownership on the presented body felt strong pain.

On the other hand, the MR technique decreased the inherent ownership of the body leading to the sensation that one's own limbs are not part of one's body. The sensation of intangibility had more of an impact because the participants still believed that the presented limb was their own, even if the sensation of ownership had decreased. We should carefully consider which type of ownership we manipulate, the elicited ownership such as in previous studies or the inherent ownership such as in this study (cf. Kannape et al., 2019); the manipulation may have different effects.

The Mental Model of One's Body

We could change pain perception by changing the properties of the mental model of the body. The results of this study can be explained as a top-down effect on perception (Gregory, 1997; Martini et al., 2013; Senna et al., 2014). The feeling of intangibility in this study meant the sensation that one's body had become something cannot be touched, like that of a ghost. Such creatures are believed to be unable to feel pain. The illusion of transparency triggered this perception, resulting in decreased pain.

Changes in other properties, such as an iron skin, might have the same effect as transparency. This top-down effect could also have an opposite effect: For example, if the material of body is changed to something fragile, such as glass, and the body is hit by a hammer, participants may perceive more pain that with their normal bodies. In addition, some changes have the potential to change task performance.

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