Pseudo-haptic Heaviness Influenced by The Range of the C/D Ratio and the Position of the C/D Ratio within a given Range

Takahiro Kawabe, *Member, IEEE,*, Yusuke Ujitoko, *Member, IEEE,*

***Abstract*—Pseudo-haptic heaviness refers to the illusory sensation of heaviness caused by a dissociation in amplitudes between object movements on a screen and users' motor actions. The amplitude ratio of object movements to the user's actions, the so-called C/D ratio, is a powerful determinant of pseudo-haptic heaviness. According to previous studies, perceptual judgments for a given stimulus value are influenced by the position of the value within a given stimulus range, while no studies have shown the same to be true for pseudo-haptic heaviness. The present study examined whether pseudo-haptic heaviness determined by the C/D ratio was influenced by the range of C/D ratios, and also, by the position of the C/D ratio within a given range. Participants were asked to drag and lift a square on the screen up to a target line and then rate its heaviness; the range of C/D ratios was controlled as a between-participants factor. We observed a phenomenon whereby both the range and position of the C/D ratio influenced the rated heaviness. This phenomenon was clearly established over 8 experimental trials. We conclude that both the C/D ratio range and the position of the C/D ratio within a given range are determinants for pseudo-haptic heaviness.**

***Index Terms*—pseudo-haptic heaviness, the range of C/D ratio, position in C/D ratio range, human perception, 2D display**

I. Introduction

PSEUDO-HAPTIC FEEDBACK [1], [2] is an information presentation technique for providing users with various object-related sensations such as heaviness [3]–[7], softness [8]–[11], texture roughness [12], friction [13], and so forth. Such sensations are generated on the basis of the cross-modal integration of sensorimotor signals from users' motor actions with the sensory feedback provided in response to them [14], [15]. In particular, the space-time relationship of the sensorimotor signals plays a critical role in determining the strength of pseudo-haptics as described below. Previous studies [5], [6], [16] have shown that the relative speed of an object's movement on a monitor in relation to the motor action applied in the physical space to cause the object to move determined the sensation of heaviness for the object. Specifically, lower ratios of object movement to hand movement tend to produce an impression that the object is heavier. The relative speed is often described proportionally by a control-display (C/D) ratio. However, the precise definition of the C/D ratio varies across studies; in our definition for this study, the C/D ratio increases with the relative speed of the cursor (or the object) on the monitor in relation to the user's motor action. (Note that the ratio should more properly be called the D/C ratio, not the C/D ratio. We refer to it as the C/D ratio, following the practice of previous studies [16]–[18]).

Although previous studies have repeatedly reported the significant role of the C/D ratio in the determination of object-related sensations such as heaviness, it was unclear how the sensations were influenced by the position of the C/D ratio within the given range that users experienced. Previous studies have shown that perceptual judgments for an identical stimulus value were biased by the position of the value within its range. For example, the weight (estimated in grams) of a real object (i.e., not pseudo-haptic heaviness) was judged to be greater when the object was presented among objects having lighter weights than when it was presented among objects with heavier weights [19], [20]. In addition to weight judgments for a real object, a similar effect of the distribution of stimulus values on perceptual judgment has been reported for the sweetness of a drink [21], the size of an object [21], the loudness of a tone [22], [23], and so forth. It was still unclear whether the same effect shown in previous studies [19], [20] could be observed for pseudo-haptic heaviness as for assessments of the weight of a real object – namely, that pseudo-haptic heaviness was also influenced by the position of the C/D ratio within its range.

The purpose of the present study was two-fold. The first purpose was to examine whether pseudo-haptic heaviness was influenced by the position of the C/D ratio in its range. In the experiment, the different groups of participants were tested with stimulus sets with different ranges of C/D ratios. The important point was that, as shown in Figure 1, every stimulus set contained a specific value (0.6) of the C/D ratio. By employing stimulus sets with different ranges of C/D ratio, we were able to examine whether pseudo-haptic heaviness with a C/D ratio of 0.6 was influenced by differences in the ranges of the C/D ratios among the stimulus sets. It was expected that as the 0.6 ratio was located at the lower end of the given C/D ratio ranges, the pseudo-haptic heaviness would be greater (see the caption in Figure 1 for detail). The ratio 0.6 was chosen because preliminary observations revealed that this ratio was the midpoint of the C/D ratio range within which users could comfortably operate an object with a mouse.

The second purpose was to check whether pseudo-haptic heaviness was influenced by the difference in the level of the C/D ratio within the given ranges. Based on previous studies [3]–[7], it was expected that a C/D ratio range involving

T. Kawabe and Y. Ujitoko are with NTT Communication Science Laboratories, 3-1, Morinosato Wakamiya, Atsugi, 243-0033, Kanagawa, Japan
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higher ratios (e.g., 0.6-1.0) would produce the sensation of a lighter object than a C/D ratio range involving lower ratios (e.g., 0.2-0.6). Moreover, Weber's law and Fechner's law [24] predict that the variation of rating scores within a range would depend on the level of the C/D ratio within the given range. That is, as the level of the C/D ratio increased, the variation would be smaller because the discriminability of the ratio would likely be decreased.

Section II describes related previous work. Section III describes our user experiment. Finally, Section IV describes the significance and the limitations of the present study and several issues that can be assessed in future studies.

II. Related Work on the Effect of Stimulus Range on Perceptual Judgments

It has been shown that a rating score for a certain stimulus value is influenced by the range of stimulus values in a stimulus set [25], [26]. For example, a previous study [26] showed that the size of a square or the number of dots presented was reported to be greater when identical stimulus values were tested within a stimulus set with low rather than high ranges of stimulus values. As described in the Introduction, similar phenomena have been shown for the weight judgment of real objects, the sweetness of a drink, and the loudness of a tone [21], [22]. Another previous study [23] also showed that even when the mean stimulus value was constant, the range of stimulus values in a stimulus set drastically altered the slope of the rating scores as a function of the stimulus value. Specifically, the slope was steeper as the range of the stimulus values became narrower. The results of previous studies indicate that the judgment of magnitude for a specific stimulus value is influenced by the position of the value within the range of a given stimulus set.

On the other hand, no previous studies have posed the question of whether pseudo-haptic heaviness is influenced by the position of a C/D ratio within its given range. The following user experiment was designed to answer that question.

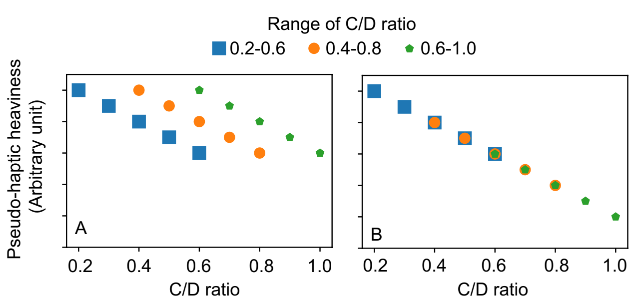

Fig. 1. Schematic figures describing our prediction. If pseudo-haptic heaviness is determined by the position of the C/D ratio within its given range, the result will be as shown in (A). On the other hand, if it is determined solely by the C/D ratio irrespective of its range, the result will be as shown in (B).

III. User Experiment

A. Participants

In total, 187 people participated in the experiment. The participants were recruited online by a crowdsourcing research company in Japan and were paid for their participation. Only people who could participate in the experiment using their own personal computers with a computer mouse were recruited and they were unaware of the specific purpose of the experiment. Ethical approval for this study was obtained from the ethics committee at Nippon Telegraph and Telephone Corporation (Approval number: R02-009 by NTT Communication Science Laboratories Ethics Committee). The experiment was conducted according to principles that have their origin in the Helsinki Declaration. Written informed consent was obtained from all participants in this study.

B. Design and Condition

Using a between-participants design, we tested the effect of C/D ratio range on pseudo-haptic rating scores. The participants were assigned to one of three groups that were tested with different C/D ratio ranges. The group assigned to the 0.2-0.6 C/D ratio range condition [0.2, 0.3, 0.4, 0.5, and 0.6] consisted of 63 participants (31 females) whose mean age was 35.95 (SD: 8.76). The group assigned to the 0.4-0.8 C/D ratio range condition [0.4, 0.5, 0.6, 0.7, and 0.8] consisted of 62 participants (32 females) whose mean age was 35.57(SD: 8.73). The group assigned to the 0.6-1.0 C/D ratio range condition [0.6, 0.7, 0.8, 0.9, and 1.0] consisted of 62 participants (32 females) whose mean age was 35.10 (SD: 9.17).

C. Procedure

1) Apparatus: This experiment was conducted online. Participants were required to use a personal computer with a computer mouse for the experiment. It was not possible to participate in our experiments using either smartphones or tablet PCs because our experimental script would not work on those devices. The mean frame rate of the participants' computer monitors was was 58.42Hz with a standard deviation of 6.38 Hz. We assembled our experimental website by using p5js (https://github.com/processing/p5.js). Although we did not measure network speeds in each participant's environment, it was not expected that the latency for stimulus presentation would be large since our experimental program was assembled with the Java scripting language, which ran locally on the participant's computer and thus the program did not communicate with our server during the experiment. For this reason, network communication states in the participant's environment did not affect the performance of our program. We provided the participants with a URL link to our experimental website. The participants visited the website and performed the experimental task.

2) Card Size Matching: Before performing the practice and main trial sessions, participants conducted a card size matching task in which they adjusted the size of a rectangle on their display so that the rectangle had the same size as a credit card or any other identically-sized card. By asking the participant to do this, we could account for the pixel size of the monitor that the participant used for the experiment, as reported in previous studies [27]–[29].

3) Practice Session: After completing the card size matching task, the participant moved on to a practice session. This session consisted of two trials each with the lowest and highest C/D ratios in the given C/D ratio range. The participant was asked to drag and lift a square up to a target line using the computer mouse (see Figure 2). We believe this task represents a typical behavior for users dragging an object in a graphical user interface. After the square reached the target line, the participant was asked to release the button of the mouse. Immediately after the participant released the square, the stimuli disappeared, and instead, five buttons appeared. The participant was asked to rate the strength of the heaviness sensation for the square on a 5-point scale. The next trial began after they had clicked one of these rating buttons.

While the participant was not dragging the square, the cursor speed was determined by the default setting of the operating system of the participant's computer. We refer to the cursor speed based on the setting in the operating system as the "default speed". While dragging the square, the cursor position relative to the square was fixed at the location within it where the participant clicked to start dragging it. Moreover, the cursor speed while dragging the square was set at the default speed multiplied by the C/D ratio. Thus, when the C/D ratio was 1, the cursor speed was identical to the default speed of the cursor. When the C/D ratio was below 1, the cursor speed was lower than the default speed of the cursor.

4) Main Session: After the participant had completed the practice session, the main session was initiated. The participant's task in the main session was identical to the one in the practice session. Each participant performed 20 trials consisting of the four repetitions of the 5 levels of the C/D ratio. The order of the trials was not blocked, but rather randomized within and across the participants. The experiment lasted 5 to 10 minutes depending on the participant.

D. Measures

Our aim was to analyze how the rating scores for pseudo-haptic heaviness with the C/D ratio 0.6 differed among the participant groups. We also wanted to check the effect of trial blocks on the variation in pseudo-haptic heaviness to understand how quickly the observed effect occurred. Additionally, we wanted to examine the mean rating scores as well as the variation of rating scores within a given C/D ratio range.

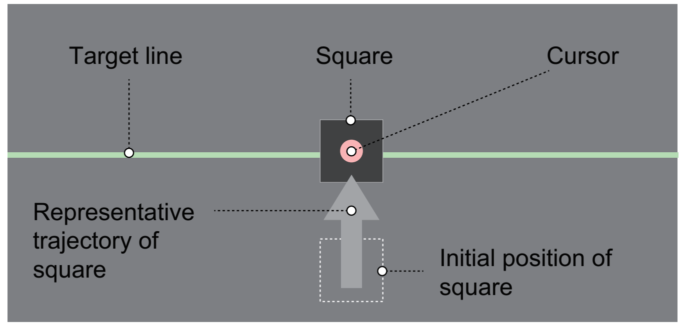

Fig. 2. Schematic descriptions of stimuli. Stimuli consisted of a square, the cursor (a pink disk), and a target line. The square, which was 1.1 cm (width) $\times$ 1.1 cm (height), had an RGB intensity of [64, 64, 64]. At the initiation of each trial, the square was positioned so that its center was 4.4 cm below the center of the monitor. The target line, which was 11.6 $\times$ 0.1 cm, was centered at 2.2 cm below the center of the display. The RGB intensity of the target line was [192, 192, 192] when the square did not overlap the target line but changed to an RGB intensity of [192, 255, 192] when this overlap occurred. While being clicked/dragged, the square was bordered by a 1-pixel white line with an RGB intensity of [192, 192, 192]. The cursor had a circular shape with an RGB intensity of [246, 186, 187]. The background had an RGB intensity of [128, 128, 128]. The RGB intensities and shapes of the visual stimuli were chosen to ensure high visibility of the components even when they were superimposed on each other.

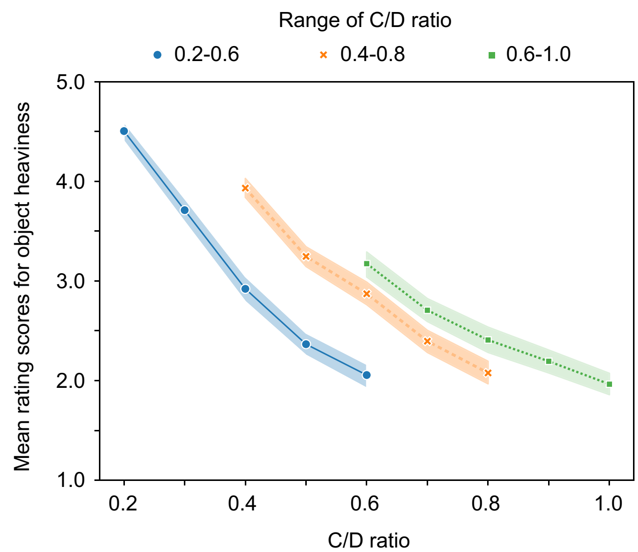

Fig. 3. Results of our user experiment. Rating scores for object heaviness are plotted as a function of the C/D ratio. Error stripes denote 95% confidence intervals.

E. Results and Discussion

1) Effect of the Position of the 0.6 C/D Ratio: The rating score for each condition was averaged across the four repetitions for each participant. Figure 3 shows the mean rating scores for pseudo-haptic heaviness as a function of the C/D ratio for each C/D ratio range. We checked whether the rating scores were determined by the position of the C/D ratio within its given range. Specifically, we analyzed whether the rating score for the condition with a C/D ratio of 0.6 differed among the C/D ratio range conditions. Since rating scores do not follow a normal distribution, it is not appropriate to parametrically assess the statistical aspect of the scores in their raw form. Hence, we transformed the rating scores by using an aligned rank transformation (ART) [30], and then conducted an analysis of variance (ANOVA) with the C/D ratio range as a between-participant factor. The main effect of the C/D ratio range was significant [F(2,184) = 37.335, p $<$ .0001, η_p^2 = 0.289]. Using the ART-C [31], we conducted multiple comparison tests, which showed that the rating scores for the C/D ratio of 0.6 in the 0.2-0.6 range were significantly greater than those in the 0.4-0.8 and 0.6-1.0 ranges, while the difference in the rating scores between the 0.4-0.8 and 0.6-1.0 ranges did not reach a significance level, p = .05 (Table I).

The results showed that the position of a C/D ratio within its given range significantly influenced the rating scores for pseudo-haptic heaviness. Specifically, rating scores for pseudo-haptic heaviness rose as the position of a C/D ratio within its range became lower. The results indicate that in addition to a heaviness sensation for real objects [19], [20], pseudo-haptic heaviness for a virtual object is also affected by the position of a C/D ratio within its given range.

TABLE I
THE RESULTS OF MULTIPLE COMPARISON TESTS FOR MEAN RATING SCORES WITH A C/D RATIO OF 0.6 AMONG PARTICIPANT GROUPS TESTED WITH DIFFERENT C/D RATIO RANGES.

Pair	DF	t-ratio	p value	Cohen's d
0.2-0.6 v.s. 0.4-0.8	184	6.052	<0.0001	1.082
0.2-0.6 v.s. 0.6-1.0	184	8.357	<0.0001	1.495
0.4-0.8 v.s. 0.6-1.0	184	2.296	=0.0684	0.412

2) Effect of Trial Blocks: It is important to establish when during the 20 trials the position of the C/D ratio within its given range began to have an effect. To answer this question, we divided the rating scores with the 0.6 C/D ratio into five trial blocks, each of which involved four sequential trials. The variation of the rating scores among the trial blocks is shown in Figure 4. Using the rating scores, we conducted a two-way ANOVA with the C/D ratio range and the trial block as between-participant factors. The main effect of the C/D ratio range was significant [F(2,541) = 56.848, p < .0001, η_p^2 = 0.173]. Multiple comparison tests (Table II) showed that each C/D ratio was significantly different from the others. On the other hand, the main effect of the trial block was not significant [F(4,541) = 2.106, p = .0787, η_p^2 = 0.015]. Interaction between the two factors was significant [F(8,541) = 3.664, p = .0003, η_p^2 = 0.051].

We further analyzed the simple main effect of the significant interaction. Since the volume of the results is large, we provide the details of this analysis in the section Supplementary data 1. Here we briefly describe the significant results. The simple main effect of the trial block was significant only with the 0.2-0.6 C/D ratio range. Multiple comparison tests showed that with this range, trial block 1 was significantly different from blocks 3 and 4. The simple main effect of the C/D ratio range was significant with blocks 2, 3, 4, and 5. According to multiple comparison tests, the 0.2-0.6 range was significantly different from the 0.4-0.8 and 0.6-1.0 ranges. Uniquely with block 3, the 0.4-0.8 range was also significantly different from the 0.6-1.0 range.

The results showed that the effect of the position of the C/D ratio within its given range was not observed in the initial four trials. The effect became significant in the following trial blocks. The results indicate that the brain establishes internal response criteria for a stimulus range quickly (with less than eight samples) and uses the criteria to perceptually judge each stimulus value.

3) Effect of C/D Ratio Range on Overall Rating: We examined whether the mean rating scores were different among participant groups tested with different C/D ratio ranges. The main effect of the C/D ratio range was significant [F(2,184) = 18.653, p < .0001, η_p^2 = 0.168]. Using the ART-C [31], we conducted multiple comparison tests with the Bonferroni correction, which showed that the rating scores for a certain

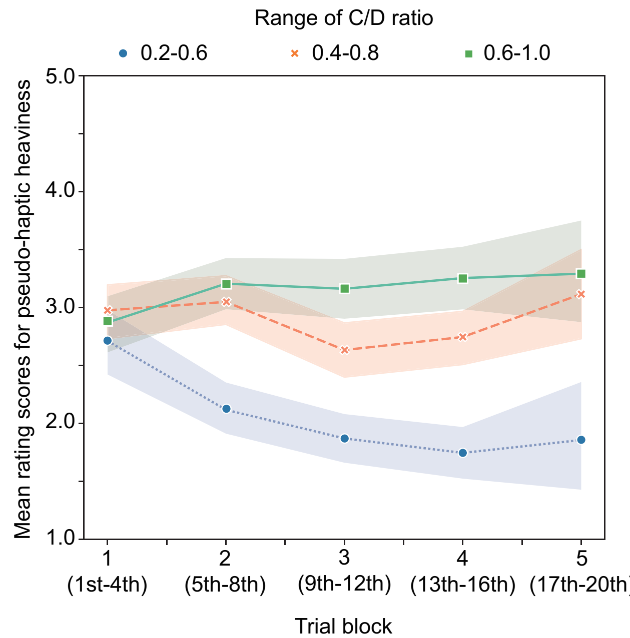

Fig. 4. The variation of rating scores with the 0.6 C/D ratio among trial blocks for each C/D ratio range. Error stripes denote 95% confidence intervals.

TABLE II
THE RESULTS OF MULTIPLE COMPARISON TESTS FOR MEAN RATING SCORES WITH A C/D RATIO OF 0.6 AMONG PARTICIPANT GROUPS TESTED WITH DIFFERENT C/D RATIO RANGES WHEN TRIAL BLOCKS ARE CONSIDERED.

Pair	DF	t-ratio	p value	Cohen's d
0.2-0.6 v.s. 0.4-0.8	541	7.263	<0.0001	0.812
0.2-0.6 v.s. 0.6-1.0	541	10.497	<0.0001	1.199
0.4-0.8 v.s. 0.6-1.0	541	3.571	=0.001	0.386

C/D ratio range were significantly different from those in the other ranges (Table III).

The results indicate that the overall rating scores for pseudo-haptic heaviness vary with the level of C/D ratio within its range, consistent with the findings in previous studies [5], [6], [16].

TABLE III
THE RESULTS OF MULTIPLE COMPARISON TESTS AMONG THE PARTICIPANT GROUPS FOR MEAN RATING SCORES.

Contrast	DF	t-ratio	p value	Cohen's d
0.2-0.6 v.s. 0.4-0.8	184	2.543	=0.0355	0.4548
0.2-0.6 v.s. 0.6-1.0	184	6.083	<0.0001	1.0882
0.4-0.8 v.s. 0.6-1.0	184	3.527	=0.0016	0.6333

4) Variation of Pseudo-haptic Heaviness within Each Range: As described in the Introduction, the Weber ratio predicted that the variation in rating scores within each range would be smaller for higher levels of the C/D ratio within the given range. To quantify the variation in each range, we calculated the "variation index" (Figure 5) by subtracting the rating scores for the highest C/D ratio within a range from the scores for the lowest one in that range. We conducted an ANOVA with the C/D ratio range as a between-participant factor. The main effect of the C/D ratio range was significant

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[F(2,184) = 32.607, $p < .0001$, $\eta_p^2 = 0.262$]. As shown in Table IV, multiple comparison tests showed that the variation index for a certain C/D ratio range differed significantly from that for the other C/D ratio ranges.

The results indicate that pseudo-haptic heaviness within each C/D ratio range is influenced by the discriminability of the C/D ratio.

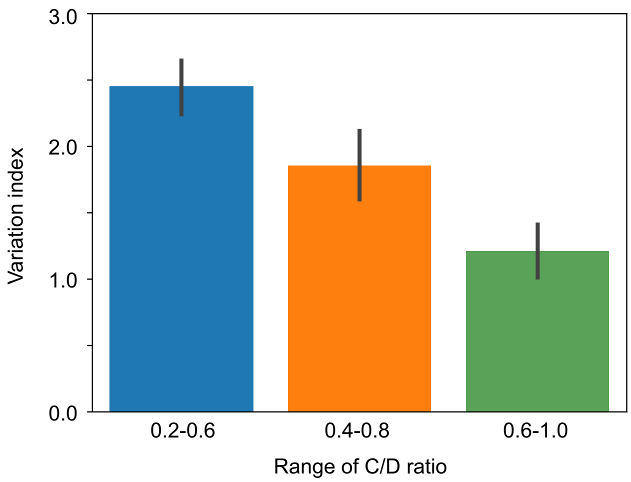

Fig. 5. Variation index (i.e., the variation of rating scores within each range of the C/D ratio). Error bars denote 95% confidence intervals.

TABLE IV
THE RESULTS OF MULTIPLE COMPARISON TESTS AMONG THE PARTICIPANT GROUPS FOR THE VARIATION INDEX.

Pair	DF	t-ratio	p value	Cohen's d
0.2-0.6 v.s. 0.4-0.8	184	3.943	=0.0003	0.705
0.2-0.6 v.s. 0.6-1.0	184	8.075	<0.0001	1.444
0.4-0.8 v.s. 0.6-1.0	184	4.116	=0.0002	0.739

IV. General Discussion

A. Significance

The main significance of the present study has been to show that the pseudo-haptic heaviness sensation was influenced concurrently by the C/D ratio range and the position of the C/D ratio within a given range. Consistent with previous studies, a C/D ratio range involving higher ratios produced lower rating scores for pseudo-heaviness. Moreover, as expected, a C/D ratio range involving higher ratios showed lower variations of rating scores within the range than those involving lower ratios. Importantly, the position of the C/D ratio within its given range also influenced the mean rating scores. Specifically, a lower position in the range produced higher rating scores for pseudo-haptic heaviness. Due to the concurrent involvement of the C/D ratio range and the position of the C/D ratio within that range, the obtained results did not match the predictions in either Figure 2A or Figure 2B, but instead fell into a pattern in between.

The results of the present study may be an important source of information for engineers who wish to provide users with certain specific levels of pseudo-haptic heaviness for several different objects. Conventionally, engineers assume that a specific level of the C/D ratio will produce a specific level of pseudo-haptic heaviness. However, according to our results, this assumption is not always valid because, among multiple objects being compared, pseudo-haptic heaviness will be influenced by the position of the C/D ratio within its given range.

B. Limitations and Future Issues

Finally, we would like to mention several limitations of the present study and some issues to be addressed in future studies.

Because the present study adopted a between-participant design, it is unclear whether similar results would be obtained when different ranges of the C/D ratio were tested over time with a single participant. Future studies may check whether the pattern of rating scores changes with the range of the C/D ratio when the different ranges are tested in different sessions but with the same participant. Moreover, since we did not investigate any condition in which the cursor speed was higher than the default speed, it is difficult to know what effect this would have. We did not measure the cursor speed for each participant's computer individually, and it is unclear how individual differences in cursor speed might have influenced the determination of the heaviness sensation. This is one fascinating issue for future investigation.

Though we manipulated the C/D ratio range, an interesting direction for further study would be to examine how the size of the range influences the results. As described earlier, a previous study [23] has shown that the size of the range of stimulus values altered the slope of the rating scores as a function of the stimulus value, even when the mean stimulus value was constant. In future studies, it will be possible to check how the size of a C/D ratio range influences the slope of the rating scores of pseudo-haptic heaviness as a function of the C/D ratio.

As we have already mentioned, differences between the monitors used by the participants are unlikely to have influenced the participants' performance because we matched the stimulus sizes across the environments of the different participants, as described above. That said, it is nevertheless a critical limitation that we did not control the experimental apparatus among the participants. Moreover, though we recruited participants who would use a personal computer with a computer mouse to perform our task, we did not verify whether they actually used a mouse or a trackpad (common in laptop computers) in the experiment. We also did not control the viewing distance.

It is also one of the limitations of the present study that we did not check each participant's previous experience of the pseudo-haptic effect. Past experience with the pseudo-haptic effect might cause a difference in the discriminability of the effect. For example, it might be easier for experienced participants to interpret the difference in the cursor speed as an indication of a difference in heaviness. Indeed, a previous study [32] has reported individual differences in the discriminability of the pseudo-haptic effect. Thus, future studies may require checks as to whether individual differences have affected the results and how these differences can be explained.

It would also be interesting to investigate whether, in addition to heaviness, other pseudo-haptic sensations such as stiffness and roughness are also determined based on the C/D ratio range and the position of the C/D ratio within its range.

Finally, one could point out a problem in the fact that we did not test whether the effect on pseudo-haptic heaviness of the position of the C/D ratio in its range could be observed even when participants were asked to judge the heaviness by using an external reference such as the weight of a real object. Since we examined pseudo-haptic heaviness using only a rating scale, we must admit that the scope of the results in the present study is limited to situations where users are expected to internally establish some response criteria within a given C/D ratio range. We believe that any application implementing pseudo-haptic heaviness among several objects requires the internal establishment of response criteria about which feedback corresponds to a light or heavy sensation. Thus, we believe it was valid for the present study to use a rating scale. Nevertheless, it would be interesting to check whether similar results are observed when the participant is asked to report the degree of pseudo-haptic heaviness by comparing the sensation with the heaviness of an actual object, whereby the participants would not seem to require a number of attempts to establish internal response criteria for a given range of stimuli. On the other hand, even if similar results are not observed when the heaviness of an actual object is used as a response criterion, that does not affect the interpretation of our results, because the main contribution of this study is to show that the internal establishment of the response criteria for the pseudo-haptic heaviness occurred without an external reference.

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