Delayed visual feedback of an agent keystroke causes illusory heaviness and stiffness

Takumi Yokosaka and Takahiro Kawabe

NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, 3-1

Morinosato-Wakamiya, Atsugi, Japan.

Abstract

Imposing a delay between an action (e.g., a limb movement) and its related visual feedback (e.g., a cursor movement on the display) induces a peculiar sensation of heaviness or stiffness. Earlier studies have examined this delay-induced heaviness or stiffness sensation in relation to the non-arbitrary causal relationship between an action and its effect. Here, "non-arbitrary causal relationship" means that an agent's action produces a specific and deterministic pattern of visual feedback; for example, a leftward limb movement consistently and deterministically causes a leftward visual motion. In modern graphical user interfaces, on the other hand, users often control visual information by pressing keys, wherein the relationship between the keystroke and the change in visual information is arbitrary. The present study examined whether the sensation of heaviness/stiffness could be caused when an agent's keystroke produced a delayed arbitrary visual feedback. Participants were asked to press and hold down an assigned key to cause temporal luminance changes in a square centered on the display, which were arbitrary visual feedback of their keystroke. Not only the onset delay of the temporal luminance change from the participant's keystroke but also the speed of the temporal luminance change were examined as a visual cue to heaviness/stiffness. In Experiment 1, the participants' task was to give a rating for the strength of the heaviness and stiffness perceived when they pressed the key. Our results showed that the heaviness and stiffness ratings increased as the delay increased and decreased as the speed increased. To check whether the manipulation of the delay and speed of the visual feedback

caused changes in the subjective evaluation of sensorimotor incongruence, in Experiment 2, we asked the participants to give a rating for the sense of agency. The rating scores decreased as the delay increased and increased as the speed increased. The rating scores for the illusory heaviness/stiffness were negatively correlated with the rating scores for the sense of agency. We discuss that the brain determines the heaviness and stiffness during an agent's keystroke based on internalized statistics relating to the delay and speed of the action feedback.

¶section{Introduction}

In various human-machine interfaces, we perceive a causal relationship between our actions and the sensory feedback they trigger. For example, when a keystroke causes a change in the visual display, we may feel as if we were the one who caused the change. This sort of feeling is called a "sense of agency" ¶cite{Farrer_Franck_Georgieff_Frith_Decety_Jeannerod_2003, Gallagher_Gallagher_2000, Jeannerod_2003}.

Stimulus parameters to determine the sense of agency have been examined in perceptual and cognitive studies. In particular, a delay between an action and its effect is a contributing factor to a deterioration in the sense of agency ¶cite{asai_relationship_2007,Farrer2013, Kawabe2013, Kawabe2013_concog, sato_illusion_2005,shanks_temporal_1989, Wen_Yamashita_Asama_2015, wen_influence_2015}.

There are several explanations for the effect of delayed feedback on the sense of agency. First, the majority of studies assume that the brain has a comparator for predicted and actual sensory feedback of an action. When the comparator detects a delay between an action and its feedback, the brain interprets that the feedback is not triggered by the an agent's action and tries to calibrate the prediction system for future feedback (¶cite{Blakemore_Wolpert_Frith_1998, Blakemore_Frith_Wolpert_1999, Chambon_Sidarus_Haggard_2014, haggard_voluntary_2002, Swiney_Sousa_2014} but also read ¶cite{synofzik_beyond_2008}). Another line of study tries to explain the sense of agency in terms of

cross-modal grouping. Specifically, with a large temporal separation between an agent's keystroke and the feedback it triggers, cross-modal perceptual grouping (or cross-modal perceptual correspondence between them as suggested by ¥cite{fujisaki_feature-based_2007,nishida_marker_2002}) is impaired and this perhaps reduces the sense of agency ¥citep{Kawabe2013}.

A delay between an agent's action and the visual feedback of her/his body parts also induces sensations of heaviness and stiffness in relation to the feedback. For example, using an experimental setting in which an agent's hand position was displayed as a cursor, ¥cite{Honda2013} showed that a larger delay of the cursor feedback could produce a greater sensation of cursor heaviness. When adding a delay to visual feedback of a participant's hand image while she/he periodically moved their hand, ¥cite{Osumi2018} observed that the participant reported that her/his limb became perceptually heavier as the visual feedback delay was increased. Using the mixed reality setting, ¥cite{Luca2011} investigated how force and/or visual delays altered the perception of object compliance and found that a visual delay led to a lower perceived sense of compliance, while a force delay led to a higher perceived sense of compliance. ¥cite{Kambara_Shin_Kawase_Yoshimura_Akahane_Sato_Koike_2013} also showed a similar relationship between force/visual delay and weight perception.

The detection of sensorimotor congruence is one of the key components of the heaviness and stiffness sensation. According to ¥cite{Honda2013}, sensorimotor incongruence due to delayed visual feedback may lead to a dissociation between predicted and actual feedback of action, which may trigger the illusory sense of heaviness (and stiffness). Currently, it is unclear what kind of mechanisms mediate the detection of sensorimotor incongruence. One candidate is brain processing in the cerebellum. ¥cite{Blakemore_Sirigu_2003} showed that activation in the right cerebellar hemisphere increased with the temporal discrepancy between an agent's action and its sensory consequence, which indicates that the cerebellum is one of the neural substrates responsible for the prediction of the sensory outcome of an agent's action. The other candidate is a cognitive or perceptual factor that possibly operates independently of sensorimotor processing ¥citep{Flanagan_Beltzner_2000}. In either case, the illusory heaviness and stiffness possibly come from the re-selection of the internal model due to sensorimotor incongruence ¥citep{Takamuku_Gomi_2015}. Illusory heaviness and stiffness of this sort has been investigated as a pseudo-haptics technique in engineering contexts ¥citep{Argelaguet2013, Punpongsanon2015, Dominjon2005, Samad2019}.

As regards illusory heaviness and stiffness, there are three important questions that need to be addressed. The first question is whether the illusory heaviness and stiffness can be produced with the visual feedback from an agent's keystroke. So far, previous studies

¥citep{Honda2013, Luca2011, Osumi2018} have examined illusory heaviness and stiffness using a non-arbitrary causal relationship between an action and its feedback. Here, "non-arbitrary causal relationship" means that an agent's action produces a specific and deterministic pattern of visual feedback; for example, a leftward limb movement consistently and deterministically causes a leftward visual motion. Hence, it was still unclear whether a delay in visual feedback could function to produce the illusory heaviness and stiffness even when the feedback was triggered by an agent's keystroke in such a way that it did not have a non-arbitrary causal relationship with the feedback.

¥cite{Frey_Hansen_Marchal_2015} showed that an arbitrary causal relationship between an agent's button press and subsequent robotic arm movements activated the right cerebellar hemisphere, which likely mediated the prediction of forthcoming sensory signals after the button press. That is, without a non-arbitrary causal relationship between an action and its outcome, the cerebellum seems to predict the timing of arbitrary feedback of an agent's keystroke. Indeed, the cerebellum also mediates the perceptual prediction of external events ¥citep{O'Reilly_Mesulam_Nobre_2008}. Since the re-selection of the internal model due to sensorimotor incongruence possibly underlies the illusory heaviness and stiffness ¥citep{Takamuku_Gomi_2015}, there is a possibility that the temporal dissociation between an agent's keystroke and the delayed visual feedback it triggers can be interpreted as stemming from physical events relevant to heaviness and stiffness even when an agent's keystroke is related to the visual feedback only in an arbitrary manner (i.e., without a spatiotemporally correlated

relationship between the action and its outcome).

The second question is whether visual factors for the perception of heaviness and stiffness can also contribute to the illusory heaviness and stiffness perceived in the feedback of an agent's keystroke.

Previous studies on material perception have shown that image speed and/or playback speed of video clips were strong determinants of apparent heaviness and stiffness ¥citem{Bi2018, Kawabe2015, Kawabe2016, Shim2009}. In visual stimuli inducing perceptual causality ¥citem{Meding2020, Michotte1963, Scholl2000, Wang2020}, movement speeds after object collision determine the perceived heaviness of the object ¥citem{Todd1982}. A previous study ¥citem{Kawabe2021} showed that a lower speed of a cursor controlled by users' keystrokes caused a stronger sense of resistance, while the resistance sensation produced by visual processing is not necessarily linked to an agent's action.

The final question is whether illusory heaviness and stiffness are related to the sense of agency. As described above, ¥cite{Honda2013} reported that the illusory heaviness for the delayed feedback of an agent's hand position was possibly due to a prediction error for the feedback. It is also well known that the sense of agency often deteriorates when the prediction error for an action feedback is large ¥citem{Chambon_Sidarus_Haggard_2014, haggard_voluntary_2002, Swiney_Sousa_2014}. In these

respects, we predicted that the illusory heaviness and stiffness would be negatively correlated with the sense of agency. Specifically, the rating scores for the illusory heaviness and stiffness would increase as the delay in visual feedback increased, while the rating scores for the sense of agency would decrease as the delay in visual feedback increased.

To answer these questions, we conducted the first experiment to examine whether illusory heaviness and stiffness could be induced by the visual feedback made by an agent's keystroke, manipulating the delay of visual feedback onsets as well as the speed of visual feedback changes. To check the relationship between illusory heaviness/stiffness and sense of agency, in the second experiment we tested how the two stimulus parameters modulated the sense of agency.

The present study used temporal luminance changes as visual stimuli. Temporal luminance changes have been found to stimulate the motion processing of the human visual system (Anstis1967, Anstis1990, Arnold1993), and thus, can be used to examine the effect of visual speed on illusory heaviness and stiffness. Because temporal luminance changes are not involved with spatial stimulus shift, the undesired effect of attentional shifts and eye movements can be reduced. Moreover, temporal luminance changes are not easily related to the spatiotemporal pattern of an agent's hand movement, and thus are useful to investigate how an arbitrary causal relationship between an agent's keystroke

and its feedback is related to the induction of illusory heaviness and stiffness.

In addition to sensations of heaviness and stiffness, we examined sensation of bumpiness as a control response condition. There was a possibility that participants may report sensations of heaviness and stiffness as demand characteristics to the parameters set by the experimenters. Bumpiness does not seem to be related to temporal luminance changes because the stimuli do not feature spatial luminance changes that can be interpreted as shading. Moreover, neither is the sensation of bumpiness related to pressing a flat key on the keyboard, which our experimental participant is asked to operate. Thus, we predicted that the temporal luminance changes would not affect sensation of bumpiness.

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¥section{Experiment1}

¥subsection{Purpose}

The purpose of the experiment was to examine whether the participants could feel heaviness and stiffness in relation to a temporal luminance change triggered by their keystrokes. In the experiment, the participants were asked to press and hold down a key on a keyboard to initiate a temporal

luminance change on a display. The delay of the onset of the temporal luminance changes from the timing of the participant's keystroke was varied between five different levels: 0, 250, 500, 750, and 1000 msec. Also, the speed of the temporal luminance change was varied by modulating the duration of the change itself between three different levels. The effects of delay and speed on the degree of perceived heaviness and stiffness were tested.

In addition, we compared the effects on the evaluations of heaviness and stiffness to those on the evaluation of bumpiness to check the possibility that any evaluation could be affected by the delay and speed in the same way as that for the heaviness and stiffness. Earlier studies [Lecuyer2008](#), [Mensvoort2008](#), [Mensvoort2010](#), [Costes2019](#) showed that the sensation of bumpiness could be generated by systematically manipulating the magnitude of displacement and size of a mouse cursor along its trajectory. Changes in the appearance of the mouse cursor may stimulate visual functions to perceive structure from motion [Andersen_Bradley_1998](#) and thus can be used as a cue to visual depth perception. On the other hand, because the onset delay of the uniform temporal change does not contribute to the perception of structure from motion, it was expected that the delay would not affect the evaluation of bumpiness. On the other hand, it was unclear whether the speed of the temporal luminance change could influence the evaluation of bumpiness. In this respect, the effect of the speed on the bumpiness perception was an exploratory component of this experiment.

¥subsection{Method}

¥subsubsection{Participants}

Three hundred and sixty-two people participated in the experiment. Participants were divided into three groups, each performing one of three tasks: heaviness evaluation, stiffness evaluation, or bumpiness evaluation. One hundred and twenty-two participants (61 females) participated in the heaviness evaluation task and the mean $\pm$ standard deviation (SD) of their age was 40.29 $\pm$ 11.52. One hundred and twenty participants (60 females) participated in the stiffness evaluation task and the mean $\pm$ SD of their age was 39.66 $\pm$ 11.07. One hundred and twenty participants (59 females) participated in the bumpiness evaluation task and the mean $\pm$ SD of their age was 40.03 $\pm$ 11.68. A Japanese crowdsourcing research company recruited the participants online and they were paid for their participation. 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 experiments were conducted according to principles that have their origin in the Helsinki Declaration. Written informed consent was obtained from all observers in this study.

¥subsubsection{Apparatus}

The experiment conducted in this study was carried out using the participants' own personal computers (PC) because our experimental script could only be run on a PC. Hence, smartphones or tablet PCs, which do not have keyboards, could not be used in this experiment. Viewing distance and screen size were not controlled because their effect was not evident in the preliminary observation provided the user used the PC normally.

¥subsubsection{Stimuli}

As shown in Figure ¥ref{fig:setup}A, the stimuli consisted of a square (100 $\times$ 100 pixels, with RGB values of [0, 0, 0] or [255, 255, 255]) centered in the display and a uniform background (with RGB values of [128,128,128]). The initial luminance of the square in RGB values was randomly set to [0, 0, 0] or [255, 255, 255] and changed toward [255, 255, 255] or [0, 0, 0], respectively, only when the participant held down an assigned key (i.e., the M key on the computer keyboard). When participants released the key before the square had finished changing its luminance, the luminance of the square returned to its initial state and the participants were asked to restart the trial. The square took 500, 1000, or 2000 milliseconds to complete the luminance change: the speed at which the luminance changed was [510.0, 510.0, 510.0]/sec (fast), [255.0, 255.0, 255.0]/sec (medium), or [127.5, 127.5, 127.5]/sec (slow), respectively. The conditions relevant to the speed of luminance change are

referred to as "speed conditions." Also, there was a programmed delay of 0, 250, 500, 750, or 1000 milliseconds for the luminance of the square to start changing after the participant pressed the key. The conditions relevant to these time lags are referred to as "delay conditions." We rendered the luminance of the square based on the time elapsed from the start of the key press, not on a frame rate basis. Therefore, the delay and duration were not substantially affected by the frame rate of a participant's PC. We preliminarily measured rough latency, i.e., how long it took for the luminance of the square to change after pressing a key, by attaching a pressure sensor to the keyboard and a CdS cell to the monitor of the author's computer. From the results of three measurements in the 0 ms delay condition, we found that the latency ranged from a minimum of 38 milliseconds to a maximum of 106 milliseconds (Figure [¥ref{fig:setup}B](#)). The latency likely stemmed from system delay and the mean $\pm$ SD of the latency for the three measurements was 76.12 ± 8.02 ms. Moreover, the averaged SD of overall duration (i.e., the time from key press to the time the luminance of the square had finished changing) was 17.86 ms, which is much shorter than the minimum difference of 250 ms between the delay conditions, and did not depend on the delay and speed conditions (see Figure [¥ref{fig:setup}C](#)). After the square had completed the luminance change, it disappeared for 500 milliseconds and then the answer screen was displayed.

¥subsubsection{Procedure}

At the beginning of the experiment, the participants were presented with written instructions that described the situation and their tasks in the experiment. After reading this, the participant pressed the space key on the computer keyboard to start the experiment. The participant's task was to hold down the M key and trigger the luminance change of the square. After the square had completed the luminance change and disappeared, the answer screen was displayed. In the heaviness, stiffness, or bumpiness evaluation task, the following instruction sentence was presented to the participants, "Rate to what extent you felt heaviness, stiffness, or bumpiness during the key press." In all tasks, participants reported the evaluation on a 5-point scale by pressing the assigned keys, wherein 5 represented the highest heaviness, stiffness, or bumpiness, while 1 represented the lowest heaviness, stiffness, or bumpiness. After reporting the evaluation, the next trial began. Each experimental condition was repeated 5 times. Thus, each participant performed 75 trials (3 speed conditions $\times$ 5 delay conditions $\times$ 5 iterations). We randomized the order of presentation every 15 trials (i.e., 3 speed conditions $\times$ 5 delay conditions). Moreover, we measured effective frames per second (efps) and calculated the averaged efps during stimulus presentation on each trial to check whether the participant's PC was not able to draw the experimental stimuli accurately due to the efps being too low.

¥subsection{Results and Discussion}

The averages (SD) of efps among participants' PCs in the heaviness, stiffness, and bumpiness evaluation tasks were 58.38 (6.69) Hz, 57.89 (7.70) Hz, and 58.29 (6.88) Hz, respectively (Figure ¥ref{fig:setup}D). The results showed that for most participants the experiments were performed at almost 60 efps.

For each condition, heaviness rating scores were averaged for each participant. Rating scores across the participants are shown in Figure ¥ref{fig:exp1-3}A. By using 'vegan' ¥citep{Oksanen2020} and 'EcolUtils' ¥citep{Salazar2020} packages of R ¥citep{R2020}, a two-way permutation analysis of variance ¥citep{Anderson2001, Anderson2013} was conducted with the duration and delay conditions as within-subject factors. The main effect of the delay condition was significant [$F = 74.24$, $p < .001$, $r^2 = 0.10$]. The main effect of the speed condition was also significant [$F = 371.32$, $p < .001$, $r^2 = 0.25$]. The interaction between them was significant [$F = 9.93$, $p < .001$, $r^2 = 0.03$]. The simple main effect of delay was also significant for all speed conditions (Table ¥ref{table:weight_delay}). The simple main effect of speed was significant for all delay conditions (Table ¥ref{table:weight_speed}).

In a way similar to the heaviness rating scores, we conducted a two-way permutation analysis of

variance for the stiffness rating scores (Figure [¥ref{fig:exp1-3}B](#)). Both of the main effects of the delay condition [$F = 28.09$, $p < .001$, $r^2 = 0.05$] and the duration condition [$F = 87.90$, $p < .001$, $r^2 = 0.08$] were significant. The interaction between them was also significant [$F = 4.66$, $p < .001$, $r^2 = 0.02$]. The simple main effect of delay was also significant for all speed conditions (Table [¥ref{table:hard_delay}](#)). The simple main effect of speed was significant for all delay conditions (Table [¥ref{table:hard_speed}](#)).

Using the bumpiness rating scores, we conducted a two-way permutation analysis of variance for them (Figure [¥ref{fig:exp1-3}C](#)). The main effect of the duration condition was significant [$F = 34.93$, $p < .001$, $r^2 = 0.04$] while that of the delay condition was not significant [$F = 2.28$, $p = .054$, $r^2 < 0.01$]. The interaction between them was also not significant [$F = 0.92$, $p = .51$, $r^2 < 0.01$].

The results showed that the rating scores for heaviness and stiffness increased with the delay between the timing of a participant's keystroke and the onset of a temporal luminance change, whereas the rating scores for bumpiness did not. This is the first evidence that humans can estimate heaviness and stiffness from a delay in visual feedback that are caused by an agent's keystroke. The results are consistent with previous studies suggesting that the brain perceptually estimates heaviness and stiffness by re-selecting the internal model [¥citep{Takamuku_Gomi_2015}](#) or by interpreting

prediction errors ¥cite{Honda2013} on the sensorimotor incongruence in terms of timing between an agent's keystroke and the feedback it triggers. In contrast, the results showing that the perception of bumpiness was not influenced by the delay in visual feedback indicate that bumpiness is not grounded in the computation of sensorimotor incongruence. The brain possibly uses different information for the estimation of bumpiness from that used for the estimation of heaviness and stiffness.

Consistent with previous studies ¥citep{Bi2018, Kawabe2015, Kawabe2016, Shim2009, Todd1982} on material perception, the speed of the feedback transition also influenced the heaviness and stiffness ratings. Specifically, the slower temporal luminance changes caused a greater perception of heaviness and stiffness. The results indicate that the illusory heaviness and stiffness on the basis of the delayed visual feedback of an agent's keystroke stem from both the re-selection of the internal model due to sensorimotor incongruence and the appearance of the feedback itself. Unexpectedly, the perception of bumpiness was influenced by the speed of temporal luminance changes. Although, at this stage, we are not able to provide a decent explanation of the effect of the speed on the perception of bumpiness, we believe that the explanation for this is beyond the scope of this experiment. Moreover, the range of rating score variations is rather smaller for the bumpiness than for the heaviness and stiffness ratings, and thus, the speed of the temporal luminance changes perhaps played only a minor role in determining the bumpiness rating. Rather, we would like to emphasize the results showing that the perception of

bumpiness was not influenced by the delay applied to the visual feedback, which indicates that the effect of the delay on the heaviness and stiffness ratings is not based on the demand characteristics.

¥section{Experiment 2}

¥subsection{Purpose}

This experiment examined how the illusory heaviness and stiffness could be related to the sense of agency. As described above, re-selection of the internal model ¥citep{Takamuku_Gomi_2015} or interpretation of prediction errors ¥citep{Honda2013} on the sensorimotor incongruence possibly underlies the illusory heaviness and stiffness. The sensorimotor incongruence undermines the sense of agency ¥citep{asai_relationship_2007,Farrer2013,Kawabe2013,Kawabe2013_concog,sato_illusion_2005,shanks_temporal_1989,wen_influence_2015,Wen_Yamashita_Asama_2015}. Taken together, a larger sensorimotor incongruence likely causes a stronger sensation of heaviness and stiffness while also causing a weaker sense of agency. Based on this idea, it was predicted that a larger onset delay of the temporal luminance changes would cause lower rating scores for the sense of agency. It was also predicted that a lower speed of the temporal luminance changes would cause the rating scores for the sense of agency since it was known that the speed of visual feedback affects the sense of agency ¥citep{Kawabe2013_concog}. Moreover, we also

expected that the rating scores for the sense of agency in this experiment would be negatively correlated with the rating scores for the illusory heaviness and stiffness. In a control condition to check whether the effect of the delay on the sense of agency (SoA) ratings stemmed from demanded characteristics, we also asked another group of participants to evaluate a background luminance change that was related neither to a participant's key press nor to temporal luminance changes in the square.

¥subsection{Method}

¥subsubsection{Participants}

Two hundred and thirty-nine people, who had not participated in Experiment 1, participated in Experiment 2. Participants were divided into two groups, each performing either of two tasks: SoA evaluation or background-luminance evaluation (i.e., the control question). One hundred and twenty participants (60 females) participated in the SoA evaluation task and the mean $\pm$ SD of their age was 39.40 ± 11.18 . One hundred and nineteen participants (59 females) participated in the background-luminance evaluation task and the mean $\pm$ SD of their age was 40.03 ± 11.18 .

¥subsubsection{Stimuli}

The stimuli in the SoA evaluation task were identical to those used in Experiment 1. On the other hand,

the background-luminance evaluation task had an additional five catch-up trials. In the catch-up trials, the initial luminance of the background with RGB values [128,128,128] changed toward [0, 0, 0] or [255, 255, 255] only when the participant held down an assigned key (i.e., the M key on the computer keyboard).

¥subsubsection{Procedure}

The procedure was identical to that used in Experiment 1 except for the following. In the SoA evaluation task, the following instruction sentence was given to the participants, "Rate the extent to which your key press appeared to causally control the luminance of the square". They reported the evaluation on a 5-point scale by pressing the assigned keys, where 5 indicated the strongest impression and 1 the weakest impression of causal control. In the SoA evaluation task, each participant performed 75 trials [(3 speed conditions $\times$ 5 delay conditions) $\times$ 5 iterations]. We randomized the order of presentation every 15 trials (i.e., 3 speed conditions $\times$ 5 delay conditions) among participants. In the background-luminance evaluation task, the following instruction sentence was given to the participants, "Rate the degree to which the luminance of the background (not the square) changed". They reported the evaluation on a 5-point scale by pressing the assigned keys, where 5 indicated the strongest impression and 1 the weakest impression of background luminance change. In the background-luminance evaluation task, each participant performed 80 trials [(3 duration conditions

$5 \times$ delay conditions $+ 1$ catch-up trial) $5 \times$ iterations]. We randomized the order of presentation every 16 trials (i.e., 3 duration conditions $5 \times$ delay conditions $+ 1$ catch-up trial) among participants.

Results and Discussion

The averages (SD) of efps among participants' PCs in the SoA evaluation and background-luminance evaluation tasks were 58.44 (7.73) Hz and 58.54 (6.26) Hz, respectively (see two plots on the right side of Figure [Fig. 4D](#)). The results showed that most participants' PC performed the experiments at almost 60 efps.

For each condition, SoA ratings scores were averaged for each participant. Rating scores across the participants are shown in Figure [Fig. 5A](#). Using the individual mean rating scores, a two-way permutation analysis of variance was conducted with the speed and delay conditions as within-subject factors. The main effect of the delay condition was significant [$F = 25.63$, $p < .001$, $r^2 = 0.05$]. The main effect of the speed condition was also significant [$F = 69.54$, $p < .001$, $r^2 = 0.07$]. The interaction between them was not significant [$F = 1.50$, $p = .135$, $r^2 < 0.01$].

We also conducted a two-way permutation analysis of variance for the background-luminance rating

scores (i.e., the control condition; Figure [Fig. 4B](#)). The main effect of the speed condition was significant [$F = 2.94, p < .05, r^2 < 0.01$] while that of the delay condition was not significant [$F = 0.05, p > 1.000, r^2 < 0.01$]. The interaction between them was not significant [$F = 0.09, p > 1.000, r^2 < 0.01$].

SoA rating scores decreased as the delay increased, which was a successful replication of previous studies showing that the delay between an action and its effect is an important factor for causal perception, i.e., sense of agency (e.g., [Sato et al. 2005](#), [Ebert 2010](#), [Kalckert 2012](#), [Kawabe 2013](#), [Rognini 2013](#), [Wen & Yamashita 2015](#)). Since the background-luminance rating scores in the control task were not affected by the delay, the results relating to SoA are unlikely to originate from unintended factors such as demand characteristics.

SoA rating scores decreased as the speed of the temporal luminance change decreased. The results are consistent with the previous study [Kawabe 2013](#) showing that sense of agency increased with the magnitude of an agent's action feedback. On the other hand, there is no *a priori* reason to assume that the speed of visual feedback influences the sense of agency. One possibility suggested by a previous study [Kawabe 2013](#) is that the larger magnitude of an agent's action feedback is perceived as an indication of the larger influence of an agent's action

on the external world. Hence, a greater speed of visual feedback might entail a stronger sense of agency.

Another possibility is that the effect of the speed of the temporal luminance change on the sense of agency came from the visual interpretation of the feedback. As described above, slower motion is a diagnostic feature for heavier and/or stiffer objects (Bi2018, Kawabe2015, Kawabe2016, Shim2009, Todd1982). In general, heavier and/or stiffer objects cannot be well controlled. As such, the visual interpretation of the feedback may determine the SoA rating.

The background-luminance rating scores also increased as the speed of the temporal luminance change increased. However, the range of the rating score variation was smaller for the background luminance change than for the sense of agency. In comparison with the scores in the catch-up trials, in which actual background luminance change occurred, the scores in the experimental trials were fairly low. Hence, we concluded that the effect of the speed of the temporal luminance change on the perception of background luminance change was small because it might be explained by a response bias or the misattribution of slow luminance change to its background.

As mentioned above, we expected that the SoA rating scores would be negatively correlated with the rating scores for heaviness and stiffness obtained in Experiment 1. To confirm this expectation, using 15 experimental conditions (5 delays $\times$ 3 speeds), we conducted a linear regression analysis of

the rating scores for heaviness and stiffness by treating the SoA scores as an independent variable (Figure [¥ref{fig:regression}](#)). The results showed that the slopes were significantly below zero in the rating scores for heaviness (slope\$ = -1.75\$, \$t(13) = -13.66\$, Bonferroni-corrected \$p < .001\$, \$R^{2} = 0.93\$), stiffness (slope\$ = -1.10\$, \$t(13) = -19.17\$, Bonferroni-corrected \$p < .001\$, \$R^{2} = 0.97\$), and bumpiness (\$slope = -0.47\$, \$t(13) = -5.92\$, Bonferroni-corrected \$p < .001\$, \$R^{2} = 0.73\$). It is worth noting that both the coefficient of determination and the absolute slope value of the fitted function are larger for heaviness and stiffness than those for bumpiness. This is possibly because the perception of heaviness and stiffness is influenced by the onset delay of temporal luminance changes, which is related to sensorimotor congruence, while the perception of bumpiness is not. These results suggest that the brain uses the delay and speed of the visual feedback to determine the sense of agency in a way similar to the estimation of heaviness and stiffness.

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¥section{General Discussion}

We found that the heaviness/stiffness evaluation for the temporal luminance changes as visual feedback of a participant's keystroke depended strongly on the delay and speed of the visual feedback.

The bumpiness and background-luminance change evaluations were not influenced by the delay of the visual feedback. Similarly to the heaviness/stiffness evaluations, the sense of agency evaluations was influenced by both the delay and speed of the visual feedback. A simple regression analysis showed that the heaviness and stiffness evaluations exhibited strong negative correlations with the sense of agency rating.

The present study offers the first evidence that the delay and speed of the visual feedback of an agent's keystroke are important parameters for the illusory perception of heaviness/stiffness. Although some previous studies in engineering contexts have shown that the change in color of a hand-shaped mouse cursor or an agent's finger when pressing a button or a real object enhanced the stiffness sensation (Argelaguet2013, Punpongsanon2015), they did not investigate the role of the delay and speed of the visual feedback in the determination of illusory heaviness/stiffness. The present study independently manipulated the delay and speed of the visual feedback and found that both parameters could strongly and interactively contribute to illusory heaviness/stiffness. Appropriately extending the parameters of the visual feedback which the present study has revealed, in the future, it may be possible to stimulate in an agent the desired level of heaviness and stiffness perception in an accurate manner.

As expected, a negative correlation was observed between the rating scores for the sense of agency

and the illusory heaviness/stiffness. The results indicate that the sensorimotor incongruence between the timing of an agent's keystroke and that of visual feedback is a key determinant of both the sense of agency and the illusory heaviness/stiffness. It remains an open question whether the negative correlation between the sense of agency and the illusory heaviness/stiffness is maintained when the range of the delay and speed of visual feedback is extended. For example, if the delay became greater than 1000 ms, it is likely that the sense of agency would be completely lost while the perceived heaviness/stiffness would start to decrease since the temporal luminance changes would no longer be attributable to the agent's keystroke. It is important to test this prediction in future studies. Another interesting direction would be to investigate how the sensorimotor incongruence in terms of spatial offset between an agent's hand and the feedback it triggers could influence the illusory heaviness/stiffness since the sense of agency is influenced by the spatial congruence between an action and the feedback it triggers (Kalckert2012, Farrer2008).

One might suspect the possibility that the delay and speed of temporal luminance changes influenced the way the participants pressed an assigned key. For example, participants might physically apply a greater force to a key when the temporal luminance changes were presented with a larger delay and/or a lower speed, and the participants may interpret the visual feedback as a result of making the keystroke with a stronger physical force, as that would imply an object/event with a stronger

heaviness/stiffness. Thus, we could conduct laboratory experiments to measure pressing forces while changing the delay and speed of the temporal luminance changes. On the other hand, even if we measured the force data during our task, it would be difficult to disentangle the following two possibilities: one possibility would be that the force change came directly from the delay and speed of the temporal luminance changes and the other possibility would be that the force change came from the illusory heaviness/stiffness. For the former possibility, it is not easy to theoretically justify why the delay and speed of visual feedback would cause a greater force to be applied to a key. For the latter possibility, the force change is the byproduct of the illusory heaviness/stiffness, and hence, the force itself cannot underlie the illusory heaviness/stiffness. Therefore, at this stage, we believe that there is not a plausible reason to investigate the effect of the force applied to a key during our task on illusory heaviness/stiffness.

We would like to discuss the role of internalized representation of the external world in the generation of illusory heaviness/stiffness. A previous study [¥citep{Takamuku_Gomi_2015}](#) argued that the brain re-selects our internal model for specific physical events on the basis of motion information in the visual feedback. In that study, the participants were asked to repeatedly perform spatially sinusoidal hand movements. A cursor was shown to the participants as visual feedback, and on some trials a delay was added to the display of the cursor. Based on the non-arbitrary relationship between an agent's

action and the feedback it triggers, the brain might be able to easily re-select the internal model on the basis of the sensorimotor incongruence. On the other hand, in the present study, the causal relationship between a participant's keystroke and the feedback it triggers was arbitrary. In other words, the outcome of action in the present study was temporal luminance changes that could stem from various physical sources and were not specifically linked with the keystroke. For such an arbitrary action-feedback relationship, it is unclear whether the explanation of a re-selection of the internal model is straightforwardly applicable to the illusory heaviness/stiffness perceived during a participants' keystroke in the present study. We speculate that rather than the re-selection of the internal model for physical events, the internal model for a general statistical relationship between the weight (or stiffness) of an object and the delay of its movement after the application of the agent's force possibly produces the illusory heaviness/stiffness for the arbitrary action-feedback causal relationship. For example, after the application of force to an object, a heavier (or stiffer) object moves (or deforms) more slowly than a lighter (or less stiff) one, and thus shows more delay in moving (or deforming) to a certain position (or shape). The brain may take advantage of the statistical relationship between the timing and speed of an action's consequence in order to judge the heaviness and stiffness of an object. To confirm this speculation, future studies need to assess how the degree of arbitrariness between an action and its feedback influences the strength of the illusory heaviness/stiffness.

Figure 1. Trial sequence of experiments. (B) Preliminary measurements of latency, which is defined as the temporal separation between the key press and the onset of luminance change under a 0 ms delay condition on the author's PC. (C) Preliminary measurements of overall duration (i.e., latency + delay + duration) on the author's PC. (D) Distribution of eFPS for each experiment.

Experiment 1 results. Box plots of (A) heaviness rating scores, (B) stiffness rating scores, and (C) bumpiness rating scores for each of the duration conditions as a function of the delay. Asterisks denote the pairs for which the means were significantly different using the EcolUtils package (Bonferroni-corrected $p < 0.05$).

{Experiment 2 results. Box plots of (A) sense of agency rating scores and (B)}

background-luminance rating scores for each of the duration conditions as a function of the delay.

Asterisks denote the pairs for which the means were significantly different using the EcolUtils package

(Bonferroni-corrected $p < 0.05$).

fig:exp4-5

Correlations plots of the rating scores for (A) heaviness, (B) stiffness, and (C) bumpiness as a function of the rating scores for the sense of agency. The black lines denote fitted lines by simple regression analysis. In each panel, 15 conditions (3 speeds $\times$ 5 delays) are plotted. All p-values were Bonferroni-corrected.

fig:regression

Table 1. Simple main effect of delay on heaviness evaluation

	F	Bonferroni corrected p	r^2
Speed = slow	7.87	< 0.001	0.05
Speed = medium	30.05	< 0.001	0.17
Speed = fast	55.56	< 0.001	0.27

Table 2. Simple main effect of speed on heaviness evaluation

	F	Bonferroni corrected p	r^2
Delay = 0 [ms]	120.98	< 0.001	0.40
Delay = 250 [ms]	106.58	< 0.001	0.37
Delay = 500 [ms]	87.76	< 0.001	0.33
Delay = 750 [ms]	58.40	< 0.001	0.24
Delay = 1000 [ms]	31.99	< 0.001	0.15

Table 3. Simple main effect of delay on stiffness evaluation

	F	Bonferroni corrected p	r^2
Speed = slow	3.06	0.04	0.02
Speed = medium	13.32	< 0.001	0.08
Speed = fast	21.47	< 0.001	0.13

Table 4. Simple main effect of speed on stiffness evaluation

	F	Bonferroni corrected p	r^2
Delay = 0 [ms]	32.94	< 0.001	0.15
Delay = 250 [ms]	29.26	< 0.001	0.14
Delay = 500 [ms]	23.94	< 0.001	0.12
Delay = 750 [ms]	11.60	< 0.001	0.06
Delay = 1000 [ms]	7.26	< 0.001	0.04

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