Categorical perception of control

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Abstract (150 words)

The self is a distinct entity from the rest of the world, and actions and sensory feedback are our channels of interaction with the external world. This study examined how the sense of control influences people's perception of sensorimotor input under the framework of categorical perception. Experiment 1 showed that the sensitivity (d') of detecting a 20% change in control from no change was higher when the changes occurred at the control-category boundary, than within each category. Experiment 2 showed that the control categories greatly affected early attention allocation even when the judgment of control was unnecessary to the task. Taking together, these results showed that our perceptual and cognitive systems are designed to be highly sensitive to small changes in control that build up to a determinant change in the control category within a relatively narrow boundary zone between categories, compared to a continuous, gradual physical change in control.

Keywords: sense of control, categorical perception, sensorimotor perception, signal detection theory, self-consciousness

Introduction

In daily life, people control the objects surrounding them, to varying degrees. The subjective feeling of controlling events and changes in the external world, through one's own actions, is called the sense of control (or, broadly, the sense of agency). The sense of control serves as an important cue to distinguish the scope of the *self*, from the rest of the world. In fact, many psychological studies have shown that the self has a privileged category in our cognitive system. For example, self-advantages have been found in multiple cognitive functions, such as memory (Rogers et al., 1977), visual search (Ma and Han, 2010; Salomon et al., 2013, 2011), and attention (Devue et al., 2009; Tacikowski and Nowicka, 2010). Many types of information, or sensory inputs with certain features, such as name, face and voice, are associated with the self. However, in the case of control, unlike the “passive” and “static” features of the self, dynamic relationships between action and sensory input serve as cues to identify the self. For example, individuals may move their bodies to trigger changes in the external world, and then evaluate that control. The sensorimotor relationship between motion/action and feedback, can be continuous in the physical world. For example, the controllability of a radio-controlled car changes gradually, according to the distance from the operator and the remaining battery power. How the cognitive system processes this “extension” remains largely unknown. Does it encode the continuous action-effect inputs as linear functions, or does it organize the inputs into meaningful (non-linear) categories, such as self or other, and control or no control? This study sheds light on the categorical perception of control, with the aim of clarifying how our cognitive system organizes the sensorimotor input that underlie the sense of control.

Many existing models for the sense of control, emphasize the role of

1 sensorimotor signals. Sensorimotor signals are continuous, as opposed to categorical
2 information, and underlie the cognitive judgment of control. For example, the comparator
3 model suggests that prediction errors, generated from discrepancies between sensory
4 prediction, based on motor commands and actual sensory feedback, diminish the sense of
5 control (Blakemore et al., 1999, 1998; Brooks and Cullen, 2013; Frith et al., 2000a,
6 2000b; Wolpert and Ghahramani, 2000). In addition to the predictive comparison
7 mechanism, Wen and Haggard (2020) showed that, after an exploration period, the
8 mechanisms that detect the regular relationship between action and feedback, contribute
9 significantly to the sense of control (Wen and Haggard, 2020). As such, most studies to
10 date have agreed that the sense of control results from sensorimotor experiences,
11 generated from continuous sensory input. However, little is known about the mechanisms
12 linking continuous sensorimotor signals and the cognitive judgment of control.

13 Humans tend to perceive the world in a meaningful way, using categories of
14 terms that are formed through evolution or learning (Livingston et al., 1998). Many
15 human perceptions are highly categorical, such as color (Bornstein and Korda, 1984),
16 speech (Liberman et al., 1957; Pisoni and Tash, 1974), and facial expression (Calder et
17 al., 1996; Etcoff and Magee, 1992; Young et al., 1997). In categorical perception, our
18 perceptual systems convert linear sensory signals into nonlinear categorical
19 representations (Goldstone and Hendrickson, 2009). Categorical classes minimize
20 within-class differences in sensory signals, while accentuating between-class differences.
21 Early categorization benefits the rapid resolution of ambiguity, and efficient decision
22 making. Once a category is formed, it becomes unnecessary to pay much attention to
23 within-category differences, and decisions based on categories or prototypes can be made
24 smoothly. Furthermore, once distinct categories are formed, changes to category

boundaries are more likely to be detected than changes to category prototypes. This is because, unlike the prototypes, boundary changes may occur across categories. For example, after becoming familiar with a picture of a sad face, distinguishing a different facial expression, like happiness, is easier than detecting an even sadder expression (Etcoff and Magee, 1992).

Categorical perception usually results in a sigmoid function, with a steep slope for subjective judgments on continuous physical changes. Categorical perception can be examined by the phenomenon that the observer's ability to perceptually distinguish things is better when things belong to different categories, rather than the same category (Harnad, 1987). Fig. 1 shows the framework of categorical perception as used in the present study. In categorical perception, people process continuous sensory input (i.e., left part of Fig. 1) into distinct meaningful classes (i.e., right part of Fig. 1). Such categorization can be highly automatic and allow rapid resolution of ambiguity in the environment, thus making it useful for efficient decision-making under a lower cognitive load. Most importantly, categorical perception shapes our perception, reducing sensitivity to within-class differences while increasing the sensitivity to between-class differences (i.e., middle part of Fig. 1). This phenomenon has been intensively studied in perceptual research (Bornstein and Korda, 1984), for features such as color, face, and language, because it involves the interplay between humans' lower-level perceptual systems and their higher-level conceptual and symbolic systems. In contrast with previous research on categorical perception, in the case of control, the input of control at the physical level involves both sensory and motor information, resulting in dynamic sensorimotor information. Sensorimotor input can be continuous at the physical level (i.e., left part of Fig. 1), but it can also be transferred into distinct categories of control at the cognitive level (i.e., right

part of Fig. 1). Most importantly, it remains unknown whether such categorization at the cognitive level indeed influences the sensitivity of sensorimotor processing at the perceptual level (i.e., middle part of Fig. 1). As an alternative hypothesis, if the sense of control is a linear function of continuous sensorimotor input, then the distances in sensorimotor input are the same, and there should be comparable discrimination sensitivities between all experimental conditions.

7

Fig. 1. Framework of categorical perception of control. The categories of control are not only meaningful classes but also strongly influence the perceptual processing of sensorimotor inputs. In our experimental tasks, participants moved a computer mouse to trigger the motion of a dot on a screen. The controllability of the dot was experimentally manipulated by changing the direction of the dot movement from the mouse movement.

1 The angular error between the mouse and the dot corresponds to the sensorimotor
2 information that determines the sense of control.

3
4 This study directly examines the above alternative hypothesis, using a control
5 discrimination task in the first experiment, to specifically examine the participants' ability
6 to detect small changes in control. The experiment focuses on whether such detection
7 difficulties differ between conditions, when the change occurs within a control category,
8 and when it occurs at the boundary of control categories. The study also examines whether
9 the implicit processing of certain differences in control is influenced by the sense-of-
10 control category. Specifically, the second experiment examines automatic attentional
11 allocation for a small difference in control between stimuli, when the cognitive judgment
12 of control is task-irrelevant. Our results support categorical perception of control at the
13 cognitive level (Experiment 1) and identify the effect of categorical perception of control
14 on implicit attentional allocation, for differences in sensorimotor inputs (Experiment 2).

16 **Experimental paradigm**

17 Participants controlled the motion of a visual stimulus, by continuously moving a
18 computer mouse. As the participants moved the mouse, the *direction* of the mouse motion
19 was combined with the direction of a pre-recorded motion (i.e., another person's motion),
20 by a percentage ratio (called the level of control), generating a direction for a new vector
21 of visual stimulus (Fig. 2). The *magnitude* of stimulus motion always corresponded to the
22 mouse movement. For example, as shown in Fig. 2, for 80% control, the direction of
23 stimulus movement was generated between the angle of the mouse movement, and the
24 pre-recorded motion, at an 80/20 ratio for each moment segment at 60 Hz. Ten thousand

motions were pre-recorded by the experimenter (Christensen et al., 2019), and a randomly selected section was used for each trial/stimulus. This paradigm provided sensorimotor input at the physical level, as a linear function of actual level of control (see Supplementary Material S1), allowing us to examine the potentially discrete or non-linear perceptual nature of control.

Fig. 2. An example of a motion combination algorithm, with 80% control. The direction of the visual stimulus (dot) on the screen (red arrow) was generated between the direction of mouse movement (α , in the left panel) and the direction of a pre-recorded motion (β , in the middle panel), with an 80/20 ratio at each moment segment (60 Hz). Each direction is represented by the deviation from the right horizontal direction (indicated by dashed lines). The magnitude (M) of the dot movement was equalized to the size of the mouse movement.

Results

Experiment 1: Categorical perception of control at a cognitive level

Participants detected if their control over a stimulus changed ($\pm 20\%$), for every six-second trial (Fig. 3A). Specifically, participants moved a dot across the screen, and

1 responded, during each trial, to see if their control over the dot's movements changed.
2 The trials were divided, and for one half, the level of control remained constant as the
3 initial control level, and for the other half, the level of control increased or decreased by
4 20%, at the midpoint. The direction of the control change was blocked and displayed on
5 screen, for participants. The d' (d-prime) of the signal detection theory (Green and Swets,
6 1966) was calculated from the responses, as an index of change detection sensitivity. The
7 initial controls, before the change, ranged in a 20% sequence, from zero to 100% (there
8 were no decreasing trials from 0%, or increasing trials from 100%). To approximate the
9 category boundaries of subjective control, all participants performed an additional control
10 rating task, moving the dot with the mouse for three seconds, and rating their control out
11 of three: 1 = no control; 2 = partial control; 3 = full control, for each trial (Fig. 3C).
12 Categorical perception predicts higher detection sensitivity (d') if such changes occur at
13 the control-category boundaries, rather than within each category of control (i.e., no-
14 control and full-control categories). However, the linear encoding of control predicts
15 comparable detection sensitivity across all conditions, because of the comparable
16 magnitudes of change in sensorimotor input.

17 First, we examined how the control ratio of the motion mixing algorithm affected
18 the participants' control rating (Fig. 2, ratio of the participant's motion to the pre-recorded
19 motion). Analysis of the data from the control rating task confirmed that the control ratio
20 linearly changed the angular error, between the directions of the mouse and dot
21 movements. That is, the error linearly decreased as the ratio increased, and vice versa (see
22 Supplementary Material S2A). Furthermore, a sigmoid function was found when the
23 rating score was plotted as a function of the angular error (Supplementary Material S2B).
24 These results suggest that the participants transformed the linear sensorimotor input (i.e.,

the angular error) into the rating score, with a nonlinear sigmoid function.

Using the data from the control rating task, the subjective boundary was estimated between the no-control and full-control ratings (Fig. 3D). Specifically, the points of subjective equality (PSEs), when participants gave 50% of the trials no-control or full-control ratings, were calculated using logistic regressions (with the generalized linear model function of the MATLAB, Statistics and Machine Learning Toolbox, R2017a, The MathWorks, Inc.). The average PSE of no control was 38.0% ($SD = 10.9\%$), and the average PSE of full control was 71.2% ($SD = 6.6\%$), indicated by the left and right vertical lines in the yellow shaded area, in Fig. 3D. The yellow area is regarded as the boundary between the no-control and full-control categories.

Next, we investigated the sensitivity to changes in control (Fig. 3A). The d' (d' -prime) of signal detection theory (Green and Swets, 1966) was calculated from the responses, as a detection sensitivity index of a 20% change in control from no change. The change in control was kept constant at 20% under all conditions. However, the actual change of sensorimotor input at the physical level, differed slightly between conditions (Supplementary Material S3). To control for the influence of unbalanced sensorimotor inputs, d' was divided by the actual change in angular error (i.e., $d'/\Delta E$, where ΔE represents the change in angular error, Fig. 3B; see Supplementary Material S4, for the raw values of d') and this value was used for all statistical analyses. The results of $d'/\Delta E$ in Fig. 3B show peaks of detection sensitivity at the boundaries of the control categories, for both a 20% increase and a 20% decrease in control, supporting the prediction of categorical perception of control. A five (comparison: 0% vs. 20%, 20% vs. 40%, 40% vs. 60%, 60% vs. 80%, or 80% vs. 100%) $\times$ two (change direction: decrease or increase) repeated-measures ANOVA revealed a significant main effect of comparison ($F(4, 72) =$

20.08, $p < .001$, partial $\eta^2 = 0.53$) and a significant interaction between change direction and comparison ($F(4, 72) = 6.45$, $p < .001$, partial $\eta^2 = 0.26$). The main effect of change direction was nonsignificant ($F(1, 18) = 0.002$, $p = .963$, partial $\eta^2 < 0.01$). The main effect of comparison showed that, although the magnitude of change in sensorimotor input was always 20%, and the influence of slightly unbalanced sensorimotor input was controlled by dividing d' with ΔE , the subjective sensitivity to change showed significant differences, depending on whether the change occurred within, or between, control categories. Because the subjective boundaries of the control categories were between 38.0% ($SD = 10.9\%$) and 71.2% ($SD = 6.6\%$), changes between 40% and 60%, and between 60% and 80%, are considered to be at the boundary. Post-hoc comparisons (Bonferroni-correction of p -value was applied, the original p values were multiplied by the number of comparisons, and the significance level was .05) confirmed that the $d'/\Delta E$ in these conditions was significantly larger than for the other conditions. For the decrease condition, the $d'/\Delta E$ of 80% to 60% change was significantly larger than 20% to 0%, 40% to 20%, and 100% to 80% changes, ($p < .001$, $p = .002$, $p = .042$, respectively), but did not significantly differ from the detection of a decrease from 60% to 40% ($p = .131$). Under the increase condition, the $d'/\Delta E$ of 40% to 60% change, was significantly larger than 0% to 20%, 20% to 40% and 80% to 100% changes, ($p = .004$, $p = .038$, and $p = .009$, respectively). However, it did not significantly differ from the detection of an increase from 60% to 80% ($p > .999$). In summary, the results of $d'/\Delta E$ revealed that detection sensitivity to small changes in control was higher at the boundaries of the control categories, than within the same control category, clearly supporting the hypothesis of the categorical perception of control.

Furthermore, the significant interaction between comparison and direction of

change of the ANOVA, revealed an effect of change direction in control, on detection sensitivity. Additionally, comparisons were made between initial control conditions, for both the increase and decrease conditions. The $d'/\Delta E$ of detecting a decrease from 100% to 80% control was significantly above zero ($t(18) = 3.60, p = .002$, Cohen's $d = 0.83$; the Holm-Bonferroni method was used for ten, one-tailed, one-sample t -tests). However, the $d'/\Delta E$ to detect an increase from 80% to 100% control was significantly different from zero ($t(18) = 1.53, p = .144$, Cohen's $d = 0.35$). This indicates that, when participants initially had higher levels of control (in the category of full control), they could detect changes toward the boundaries of control, but were insensitive to changes toward the current control category extremes. This phenomenon was also observed when people initially had low levels of control (in the category of no control). Specifically, the $d'/\Delta E$ of detecting an increase from 20% to 40%, was significantly above zero ($t(18) = 2.74, p = .013$, Cohen's $d = 0.63$). However, the $d'/\Delta E$ of detecting a decrease from 40% to 20%, did not significantly differ from zero ($t(18) = 0.97, p = .347$, Cohen's $d = 0.22$). This phenomenon indicates that the establishment of a subjective control category, selectively biases the detection sensitivity, according to the direction of change.

Exp. 1-1 Control discrimination

(A) Task

(B) Sensitivity

Exp. 1-2 Control rating

(C) Task

Fig. 3. Experimental tasks and results of Experiment 1. (A) Control discrimination task. Participants moved a mouse to trigger a six-second motion of a dot on the screen. At the end of each trial, participants made a binary judgment on whether they felt that their control over the direction of dot's movement had changed (increased or decreased) during the trial. (B) Sensitivity ($d'/\Delta E$) calculated from the response of the control discrimination task. The squares and bold lines indicate averaged $d'/\Delta E$ under each condition. Dots and thin lines indicate individual results. Error bars represent standard error. (C) Control-rating task. Participants rated their control over the dot out of three: 1 = no control, 2 = partial control, 3 = full control. (D) Proportion of each rating response (no control, partial control, and full control). Black curves represent the logistic fitting results for the no-control and full-control responses. The yellow area indicates the range between the no-

control and full-control PSEs. The left and right sides of the yellow rectangle indicate the no-control and full-control PSEs (50% threshold), respectively. Error bars represent 95% confidence intervals.

Experiment 2: Visual search task for categorical perception of control

Experiment 1 revealed the typical phenomenon of categorical perception when people detect a change in control. However, it was still unclear whether sensorimotor signals are categorically processed when they have not been transformed into subjective categories of control. Experiment 2 focused on the categorical perception of sensorimotor processing at lower levels, when the judgment of control at higher cognitive levels was unnecessary for the task.

Experiment 2 used a visual search task, whereby participants searched for a visual target from three visual distractors (Fig. 4A). The visual target was a circle with one gap to the right, and the distractors were circles with gaps on the left and right. Three out of the four stimuli (the majority of motions) moved in a uniform direction, while one stimulus (the motion exception) moved slightly differently from the other stimuli. For each trial, the visual target was either one of a majority, or the exception (Fig. 4B, see Supplementary Material S5 for a video demonstration of the movements of the stimuli).

The strategy for investigating the effect of categorical perception of control on implicit attention allocation, was as follows. Theoretically, exceptions automatically capture implicit attention, therefore, detection is quicker if the visual target is the exception (Fig. 4B, target is the exception). On the other hand, if the visual target belongs to the majority, detection takes longer (Fig. 4B, target is one of the majority). The difference in detection time, between exception and majority conditions, should reflect

the perceptual difference between exceptions and majorities (bottom of Fig. 4B). Therefore, the difference in reaction time (RT) between the exception (when the target was the exception) and the majority (when the target was in the majority) conditions, was used as index for how much attention was automatically captured, by the perceptual difference between the two. This study investigates whether this index is affected by the difference in control between the majority and exception, within the same category, or at category boundaries. There were three experimental conditions where the exception and majority were under 10% vs. 30% (no-control category), 50% vs. 70% (at the boundary of the control categories), or 80% vs. 100% control (full-control category). The categorical perception of control predicts a greater effect on RT when the control differences are at the category boundaries, than when they are within each control category. On the other hand, the linear encoding of control predicts similar effects between conditions. A baseline condition was also added to the above three conditions, to investigate the effect on the index of attentional capture, of only the visual difference between the majority and exception. At baseline, participants had 0% control of all stimuli. Rather, the direction of stimulus movement was generated by combining two randomly selected sections of a pre-recorded motion, so that the difference was 20% between the visual motion of the exception and the majority.

In all four conditions, including at baseline, the exception and majority movements were generated by combining two independent motions, and varying the ratio of the combination to create a slight difference in the direction between the exception and the majority. The combination ratios were selected to ensure that the motions of the exception and the majority shared 80% of the movement direction, and moved in different directions for the remaining 20%. This resulted in a constant difference in moving

direction between the exception and the majority, under all four conditions. At baseline, both motions were due to pre-recorded movements, and, therefore, did not correlate with the mouse movements. The three experimental conditions differed in the level of control that participants had over the exceptions and the majorities. The stimulus motions were generated from a combination of participant movements (i.e., movements of the mouse) and a section of pre-recorded motion. The visual difference was constant between conditions, as the exception and the majority always shared 80% of one motion, and moved in different directions for the remaining 20%. Additionally, the difference in sensorimotor input (i.e., the difference in angular error; see Supplementary Material S2A) was constant between the three experimental conditions, as the difference in control (i.e. the difference in how much the mouse motion was used) was always 20%.

Fig. 4C shows the change in the index of attentional capture (i.e., RT for target detection in the majority, minus the RT for target detection in the exception), according to whether the difference between the majority and the exception was within-category, or at the category boundaries. A repeated-measures ANOVA (comparison: 10% vs. 30%, 50% vs. 70%, 80% vs. 100%) revealed a significant main effect of comparison ($F(2, 38) = 12.36, p < .001$, partial $\eta^2 = 0.39$). Bonferroni-adjusted post-hoc comparisons showed that the effect of target type was significantly greater in the 50% vs. 70% condition than the 10% vs. 30% and 80% vs. 100% conditions ($p = .010, p < .001$, respectively). The results reveal categorical perception at the sensorimotor level, even when the judgment of control was unnecessary for the task. When the level of control was at the boundary of the control categories, a 20% sensorimotor difference automatically captured greater attention, compared to when the 20% sensorimotor difference was within the category of control.

1 To determine whether the sensorimotor correlations had a boosting or an
2 inhibitory effect on attention, in addition to the visual difference between the majority
3 and the exception, the performance in each of the three experimental conditions was
4 compared with the performance at baseline (green belt in Fig. 4C). Specifically, when
5 participants had no control over the stimuli at baseline, the effect of target type (majority
6 vs. exception) on RT should be due, only, to the visual differences between target types.
7 On the other hand, in the three experimental conditions where participants had some
8 control over the stimuli, the effect of target type on RT should be a combination of visual
9 and sensorimotor correlation differences. A Bonferroni-adjusted significance of .017 was
10 used for the three comparisons. There was no significant difference between baseline and
11 the 50% vs. 70% control condition ($t(19) = 2.37, p = .029$, Cohen's $d = 0.53$), but the
12 effects under the other two conditions were significantly smaller than at baseline (for 10%
13 vs. 30%, $t(19) = 6.26, p < .001$, Cohen's $d = 1.40$; for 80% vs. 100%, $t(19) = 6.02, p < .001$,
14 Cohen's $d = 1.35$). Under all conditions, including at baseline, the angular difference was
15 constantly level between the motions of the exception and the majority. In other words,
16 the visual difference under all conditions, should be comparable. The results showed that
17 sensorimotor correlation had an inhibitory effect on processing the difference between
18 the exception and the majority. When sensorimotor correlations (i.e., actual levels of
19 control) were within the same category of control (i.e., the no-control category, or the
20 full-control category), the detection sensitivity to the difference between the majority and
21 the exception was minimized, and the implicit attention allocation to the exception
22 stimulus was inhibited.

Exp. 2 Visual search

(A) Task

(B) Target types

Target in the majority (the target moved in the same direction as the other two distractors)

Target in the exception (the target moved differently from the other three distractors)

Long RT
Short RT
 $RT(\text{target in the majority}) - RT(\text{target in the exception})$
= Perceptual difference between the exception and majority

(C) Capture of attention

Fig. 4. Visual search task of Experiment 2 and the effect of target type on RT. (A) Visual search task. Participants moved a mouse to trigger the movement of four circles, to search for a circle containing one gap to the right (i.e., the visual target) as quickly as possible, and identified the visual target by pressing a number key. (B) Target type (majority or exception) in the visual task. The difference in RT for target detection between the two target types, reflects the perceptual difference between the majority and exception stimuli (see Supplementary Material S5 for a video demonstration). (C) Capture of attention measured by difference in RT, between exception and majority target conditions. Black dots and thick lines indicate averaged affects, and pink dots and thin lines indicate individual results. Error bars represent 95% confidence intervals. Dashed lines and green shading represent the baseline condition and its 95% confidence interval, respectively.

Discussion

This study reveals categorical perception of control by showing high discrimination

sensitivity between two different levels of control, when the comparison is at the boundaries of the control categories, rather than when they are within the same control category, controlling for the distance of sensorimotor input. The hypothesis of categorical perception of control is valid, both when explicit judgment of control is made, and when a difference in control attracts implicit attention. This study is the first to show that the sense of control, as an extension of self, is not a linear function of continuous sensorimotor input. Instead, there is zone of abrupt transition (i.e., a boundary), between no control and full control. People are sensitive to changes in control at the boundaries, but less sensitive to changes within each control category.

Experiment 1 used a control discrimination task. Participants determined whether their control of a moving dot changed during the trial. The $d'/\Delta E$, reflecting sensitivity to a 20% change while controlling sensorimotor input, was largest when the initial control was at an intermediate level, which corresponded to the boundaries of the control categories. In theory, extreme case of categorical perception would exhibit equivalence classes and a sharp threshold. Sensory signals reaching the threshold cause sudden and qualitative changes, while changes in sensory signals above or below the threshold, have little effect on perception. Thus, categorical perception provides us with proto-symbolic thinking (Goldstone and Hendrickson, 2009). In the case of sense of control, categorical perception provides a less ambiguous perception of full control, in relation to no control, over a wider range of sensorimotor signals (no control: 0%–38%; full control: 71%–100%), instead of only extreme cases of control (i.e., 0% and 100% control). Categorical perception allows our cognitive system to concentrate resources on narrow boundaries of control, where small changes can cause quantitative changes. This benefits the rapid allocation of attention to, potentially, the most useful and important

1 information (Wen and Haggard, 2018).

2 Experiment 1 also revealed an interesting effect of initial control on sensitivity
3 to small changes in control. If individuals already had a relatively high level of control
4 (within the full-control category), a 20% increase in control (i.e., from 80% to 100%) was
5 ignored, while an 20% decrease in control (i.e., from 100% to 80% control) was
6 significant, despite the fact that the comparisons of sensorimotor input were the same in
7 both cases. This was the case when the no-control category was initially formed, where
8 an increase from 20% to 40% control was detectable, but a decrease from 40% to 20%
9 control was ignored. The initial exploration of control during the first half of the trial may
10 have formed an initial control category, and this categorization influenced the detection
11 of changes in the second half of the trial. Once a subjective category has been formed,
12 changes in the extreme direction of the category are less detectable than changes towards
13 the boundaries. This may be because extreme changes never lead to a change of category,
14 therefore, there is minimal need to allocate cognitive resources to it.

15 Furthermore, Experiment 2 shows that categorical perception of control is valid,
16 even when the judgments of control were unnecessary and not task-relevant. Differences
17 in control at the control-category boundaries, affected early implicit attention more than
18 those within each category of control. There is a possibility that the allocation of cognitive
19 resources to sensorimotor inputs may be categorical, regardless of the cognitive judgment
20 of control. Alternatively, the results may be explained by the effect of the *automatic*
21 processing of the sense of control on attentional allocation, even when task-irrelevant.
22 Future research should consider this issue. More importantly, Experiment 2 shows that
23 this effect of categorical perception was mainly due to the inhibition of early attention
24 allocation, to differences within the same category (i.e., the comparisons of 10% vs. 30%

control, and 80% vs. 100% control). Specifically, under all conditions, the physical difference (i.e., the angular difference) between the majority and the exception was at the same level. When participants had no control over any of the stimuli, such as at baseline, the visual difference between the majority and the exception captured implicit attention. When participants had some levels of control over the stimuli under the three experimental conditions, the effects of visual differences between two within-category conditions, were weakened (i.e., the conditions of 10% vs. 30%, and 80% vs. 100%). This study falls short of revealing the mechanisms that integrate the effects of visual and sensorimotor differences, but the results suggest that the two effects are not simply summed. That is, the within-category sensorimotor differences, attenuated the visual differences, and significantly decreased the effects of the target type on RT, in the 10% vs. 30%, and 80% vs. 100% control comparisons. On the other hand, sensorimotor differences between categories (or the difference at the boundaries), did not significantly diminish the effect of the visual differences on RT. In summary, the categorization of sensorimotor correlations diminished the perceptual differences within each control category, but not at the control-category boundary.

Many previous studies of the sense of control and agency, have emphasized the role of prediction error. The comparator model suggests that control is the default, and that prediction errors (i.e., reduced control) are signals that disturb the default, triggering a significant condition. This explanation can be compared to many phenomena, such as sensory attenuation and supervised motor learning. On the other hand, when people do not have much control over the environment, compared with other uncontrollable objects, controllable objects attract attention (Kumar et al., 2015; Salomon et al., 2013; Wen and Haggard, 2018). In summary, previous studies have shown that both

controllable and uncontrollable objects can be significant, depending on the current state of control. Here, the categorical perception of control presents a framework for understanding these phenomena, suggesting that control differences across control-category boundaries are significant. When the initially formed category (i.e., the default category) is full control, a lack of control captures attention, and the sensory input in the same category is attenuated. On the other hand, when the initially formed category is no control, gaining control is then significant, captures attention, and undergoes enhanced perceptual processing. In short, the initial categories formed from control may be critical to attenuating or enhancing the consequences of subsequent actions.

In summary, this study proves the validity of the categorical perception of control, for both the sense of control at a cognitive level, and the implicit processing of sensorimotor input. When individuals interact with the external world, sensorimotor input can vary dramatically. Categorical perception helps our cognitive system allocate resources to the most critical quantitative changes in sensorimotor input. The categorical perception of control also allows us to meaningfully process the relationship between actions and changes in the external world, and these meaningful representations of control, in turn, affect our sensitivity to the consequences of our actions.

Methods

Participants

Twenty healthy participants took part in two experiments on different dates (mean age = 21.9, $SD = 1.7$, 18 males, two females, 18 right-handed participants). Two left-handed participants self-reported daily use of their right hand to manipulate a computer mouse. All participants moved the mouse, during the tasks, with their right hands. All participants had corrected-to-normal visual acuity. The exclusion criterion for Experiment 1 was a

lower detection accuracy than the chance level (less than 200 correct responses, in 400 trials). One participant met this criterion and was excluded from the results of Experiment 1 (detection accuracy = 39.8%). The exclusion criterion for Experiment 2 was less than 75% of the valid trials (i.e., trials with correct target identification and RTs within ± 3 SD from individual average). No participant met this criterion. The experiment was conducted according to the principles of the Helsinki Declaration and was approved by the Ethics Committee of the Department of Psychology at the University of Tokyo. All participants provided written informed consent, prior to participation.

Tasks

Experiment 1

In the control change detection task of Experiment 1, participants used a computer mouse to move a dot on the screen for six seconds in each trial, and made a binary judgment on whether their control over the moving direction of the dot changed (Fig. 3A). There were two increase blocks and two decrease blocks in the control discrimination task. The two types of blocks were performed in ABAB sequence, and the sequence of increase/decrease was offset between participants. At the start of each block, a message appeared on the screen, prompting participants if an increase or a decrease in control should be detected. The screen background was gray, and all stimuli and messages were displayed in black. At the start of each trial, the number of current and total trials in the block was displayed on the screen for half a second and then replaced with a 40-pixel dot. The dot remained stationary until participants started moving the mouse. The onset, offset and velocity of the dot motion always corresponded to the mouse movement, but the direction of the dot motion was a combination of real-time input from the mouse motion, and 10,000 consecutive pre-recorded motions on each refresh frame (60 Hz). Specifically, on each refresh frame, if the mouse position changed from the previous

frame, the moving angles were calculated according to the mouse movement and other pre-recorded movements, respectively. Depending on the level of control, a moving vector for the dot was generated, with a magnitude corresponding to that of the mouse movement, in a direction generated from the angle between the directions of the mouse and pre-recorded movements (Fig. 2). Finally, the moving vector was used to update the position of the dot. The raw input from the mouse movement was adjusted to 40%, to prevent the stimulus from excessive motion. In each trial, participants moved the mouse continuously and observed the direction of the dot movement. In half of the trials, the level of control over the dot remained constant, while in the other half, the level of control increased or decreased by 20% (e.g., from 20% to 40% control), halfway through the trial (i.e., three seconds from the onset of the first mouse movement). According to the block type, as participants moved the dot, and “Increase” or “Decrease” message was displayed, in dark gray at the top of the screen. Six seconds after the onset of the first mouse movement, the dot disappeared and the participants pressed one of two response keys (yes or no), in response to whether they had felt their control of the dot change, during the trial. The initial control for the increase blocks was 0%, 20%, 40%, 60%, or 80%, and the initial control for the decrease blocks was 20%, 40%, 60%, 80%, or 100%. The magnitude of change was always 20%. The starting points of the pre-recorded movements were randomly selected for each trial, and were used to ensure the smooth movement of the dot. Each block consisted of 100 trials (10 repeats of each initial control condition), and the level of control changed in 50 trials, while remaining constant at the initial control level in the other 50 trials. The trial sequence was randomly assigned for each block. A total of 400 trials were conducted against the control discrimination task. The participants performed one increase and one decrease practice block, prior to the actual task. Each

1 practice block consisted of four trials. For the increase practice block, control increased
2 from, or remained constant at, 0% or 60%. In the decrease practice block, control
3 decreased from, or remained constant at, 60% or 100%. The sequence of practice blocks
4 between participants was also offset.

5 The control rating tasks followed the control detection tasks in Experiment 1. In
6 each control rating task trial, participants rated their control of the dot's direction, after
7 moving the dot for three seconds (Fig. 3C). At the beginning of each trial, a dot was
8 displayed on the screen, and participants continuously moved a mouse to trigger the
9 movement of that dot. Three seconds after the first mouse movement, this dot was
10 replaced by a rating indication on the screen. The level of control of the dot was between
11 zero and 100%, in a 10% step range. At the end of each trial, participants rated their
12 control of the dot, from three options: 1 = no control, 2 = partial control, 3 = full control.
13 The trial sequence was randomized for each participant. Participants performed six
14 practice trials, before the actual task. For practice, the level of control was 0%, 60% or
15 100%, repeated twice each time. The practice trial sequence was randomized.

16 *Experiment 2*

17 In the visual search task of Experiment 2, participants were asked to locate a
18 circle with one gap on the right (i.e., the visual target), from a total of four circles (Fig.
19 4A). The other three circles had gaps on the left and right. The circles were 60 pixels, and
20 the widths of the circle borders and gaps were both 10 pixels. In each trial, the initial
21 positions of the circles were randomly generated, to meet the requirement that the distance
22 from the center of the screen to each circle was less than 350 pixels, and the minimum
23 distance between each circle was at least 150 pixels. There were no gaps in the circles,
24 unless they were moved. Participants were asked to move the circles by moving the

1 computer mouse, while searching for the visual target. The onset, offset and velocity of
2 all circles corresponded to the mouse movement, and the motion of the mouse had specific
3 levels of control over the circle directions. Participants were asked to press the space bar,
4 as soon as they found the visual target, which stopped the moving circles so that the gaps
5 disappeared. Numbers from one to four were displayed in the center of each circle.
6 Participants then pressed one of the four number keys (1–4) to identify the visual target.
7 If there was no response five seconds after the start of the first mouse movement, the trial
8 ended and, in this case, the visual target was skipped.

9 When participants moved the mouse, three out of four circles always moved in
10 a coherent direction, while one moved slightly differently to the others. The group in
11 coherent motion was called the majority, and the stimulus that moved differently was
12 called the exception (Fig. 4B). The visual target was either the exception or the majority.
13 Under the experimental conditions, the participants' control over the exception or the
14 majority differed by 20% (see Supplementary Material S5 for a video demonstration of
15 the visual search task). Three sets of control level were selected: 10% vs. 30%, 50% vs.
16 70%, and 80% vs. 100%. These sets corresponded to the no-control category, the
17 boundary of control-category boundaries, and the full-control category, respectively. The
18 control level for the exception was 20% more, or 20% less, than the majority (e.g., there
19 were trials where the exception was under 50% control while the majority was under 70%
20 control, and trials where the exception was under 70% control while the majority was under
21 50% control). At baseline, there were no stimuli under the control of the mouse (all were
22 under 0% control), nevertheless, the moving speed corresponded to the mouse motion. At
23 baseline, the direction of the stimulus was generated by combining two randomly selected
24 sections of a pre-recorded motion (for example, consider two other people controlling the

stimuli). The first pre-recorded motion controlled 50% of the exception (i.e., 50% of exceptions were controlled by the second pre-recorded motion), and 30% of the majority (i.e., 70% of the majority was controlled by the second pre-recorded motion). Therefore, the sensory difference between the exception and the majority was 20%, although participants had no control over the stimuli directions. In summary, there were two types of visual target: the majority or the exception $\times$ (three comparisons [10% vs. 30, 50% vs. 70%, 80% vs. 100%] $\times$ two exception control types [more or less than the majority control] + one baseline) = 14 conditions, each condition repeated 15 times, and a total of 210 trials were performed. The trial sequence was randomized for each participant. In addition, participants performed eight practice trials, with two control conditions, each repeated twice. One was the baseline condition, and the other condition controlled the exception and the majority, at 40% and 60%, respectively.

Procedure

Participants performed the experiments individually in a quiet room. They were seated approximately 60 centimeters away from a 22-inch LED monitor (DELL P2217, resolution: 1680 $\times$ 1050 pixels). The response keys on the keyboard were labelled, and the surrounding keys that weren't required for tasks, were removed to prevent accidental responses. In Experiment 1, participants first performed the control discrimination task, followed by the control rating task. The first task took approximately one hour, including instruction and practice, and the second task took approximately eight minutes. A least one week after Experiment 1, the same participants returned to the lab to join Experiment 2.

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Supplementary Materials

S1. The relationship between angular error and control level. Angular error refers to the angular difference between the direction of mouse movement and the direction of stimulus movement. The absolute value of angular error was calculated for each frame of mouse movement, and was averaged over the trials. (A) Angular error was measured by the absolute angle between the mouse movement and the visual stimulus (i.e., a dot), at 60Hz. The control level of the dot was manipulated by a motion combination algorithm (see Fig. 2). (B) The mean angular errors of 440 trials, from pilot experiments at each level of control, using the dot paradigm. The plot shows a linear correlation between the angular errors and the level of control, and lower levels of control (e.g., 0.0–0.3) increase the variance of angular error. Note that the angular errors are not completely zero, because the magnitude of mouse movement was reduced to 40% to prevent excessive movement of the stimuli, and the movement of the stimuli was rounded. This process resulted in small errors, even at the 100% control level. The MATLAB codes of the algorithm that combined the mouse movements and pre-recorded motions can be found at <http://www.robot.t.u-tokyo.ac.jp/~wen/code/>

S2. The angular error and control rating in the control rating task of Experiment 1. (A) Individual and average plots of angular error against actual control. Colors represent individual results. Open squares and black lines represent averages. These plots indicate that angular error, as a sensorimotor input, is a linear function of the actual level of control. In addition, every 20% control difference corresponds to an angular error difference of approximately 15°. (B) Individual and average plots of control rating against angular error. Colors represent individual results. Open squares and black lines represent averages. These plots show that the subjective judgment of control is a logistic-like function of continuous sensorimotor input.

S3. Change of angular error under each change condition (i.e., increase or decrease conditions). Under all conditions, the magnitude of control change was 20%. However, the actual change of angular error differed slightly between conditions. A five $\times$ two (comparisons $\times$ direction of change) repeated-measures ANOVA revealed a significant main effect of comparison ($F(4, 72) = 4.34, p = .003$, partial $\eta^2 = 0.19$), and a significant interaction between the comparison and direction of change ($F(4, 72) = 3.54, p = .011$, partial $\eta^2 = 0.16$). The main effect of direction change was nonsignificant ($F(1, 18) = 0.50, p = .491$, partial $\eta^2 = 0.03$; $M_{\text{decrease}} = 15.3^\circ, SD_{\text{decrease}} = 1.44^\circ, M_{\text{increase}} = 14.94^\circ, SD_{\text{increase}} = 0.85^\circ$). Because the physical change of control did not, as expected, remain constant between conditions, $d'/\Delta E$ was used (with ΔE representing the change in angular error), instead of raw d' , to exclude the influence of unbalanced physical changes between conditions, in all statistical analyses.

1 **S4** The d' of the signal detection theory, calculated according to the response of the control
2 discrimination task in Experiment 1. Squares and bold lines represent averaged d' in each
3 condition. Dots and thin lines show individual results. Error bars represent standard error.

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1 **S5.** Video demonstration of the visual search task. This video shows a trial where the
2 target is the exception (under the exception condition) and a trial where the target belongs
3 to the majority (under the majority condition).

4 https://youtu.be/yl6zo1X4_TU

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