Synchronous motion modulates animacy perception

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Visual motion serves as a cue for high-level percepts. The present study reports novel modulation of animacy perception through synchronous motion. A target dot moving along a random trajectory was presented. The trajectory was generated based on a variant of 1/f noise; hence, the dot could be perceived as animate. Participants were asked to rate the strength of perceived animacy and perceived intention from the target dot. Several task-irrelevant dots surrounding the target were also presented. Results indicated that perceived animacy and intention were drastically weakened when surrounding dots created synchronous motion with the target dot as compared to when surrounding dots did not create synchronous motion. A series of follow-up experiments replicated these results and revealed specific characteristics of this modulation. The present findings suggest synchronous visual motion serves as a strong modulator of animacy perception.

Introduction

Motion perception is a fundamental process of the human visual system. While motion is primarily a dimension of space and time, semantic and high-level percepts can emerge from motion cues, including material transparency perception (Kawabe, Maruya, Fleming, & Nishida, 2014), the presence and traits of biological objects (Johansson, 1973), and the causality, intention, and animacy of geometric shapes (Scholl & Tremoulet, 2000). Biological motion displays (Johansson, 1973) demonstrate that motion "unveils" the presence of biological objects and their semantic features; otherwise, we are only able to see randomly arranged and meaningless point-lights. Thus, motion perception is a fundamental visual process that plays a role in perception-action loops (Nishida, 2011). Conversely, motion also contributes to high-level percepts, including causality and animacy perception. However, our understanding of animacy perception is very limited, with the exception of knowledge regarding biological motion perception.

Discriminating animate from inanimate objects is essential to our survival, from the avoidance of potential dangers to fluent interaction and communication with the environment. Recent research highlights animacy as a significant dimension of human vision both within behavioral (Bonin, Gelin, & Bugaiska, 2013; Calvillo & Jackson, 2013; Carrozzo, Moscatelli, & Lacquaniti, 2010; Lindemann, Nuku, Rueschemeyer, & Bekkering, 2011; Nairne, Vanarsdall, Pandeirada, Cogdill, & Lebreton, 2013; Pratt, Radulescu, Guo, & Abrams, 2010) and neuroimaging studies (Konkle & Caramazza, 2013; Sha et al., 2015; Wiggett, Pritchard, & Downing, 2009). It is noteworthy that motion cues, without any additional semantic features (e.g., a face), induce animacy perception (Johansson, 1973; Scholl & Gao, 2013; Scholl & Tremoulet, 2000). Such research began in the mid-20th century (Heider & Simmel, 1944; Michotte, 1963; Scholl & Tremoulet, 2000), demonstrating that interactive motion between two or more geometric shapes sufficiently leads to the emergence of causality, intention, and animacy. Recent studies by Gao and colleagues (Gao, McCarthy, & Scholl, 2010; Gao, Newman, & Scholl, 2009; Gao & Scholl, 2011) have revisited these classical observations, revealing behavioral effects and neural correlates of perceived animacy from interactive motion displays.

Various forms of visual motion facilitate animacy perception. While previous studies have revealed that motion without additional semantic features (e.g., faces) can serve as a cue for animacy perception, interactive motion is fashioned in a way whereby motion embeds explicit semantic information, causality, or intention. For example, objects in Heider and Simmel's (1944) animation emulated social interaction between a child, a parent, and an enemy.

Recent studies focused on "chasing," whereby several distractors (sheep) move at random while one object (a wolf) traces one of the distractors. Although the chasing motion display induces animacy perception, a wolf's motion trajectory is designed to pursue a target sheep; hence, the motion display also involves a semantic relationship between these two objects (Bonin et al., 2013; Calvillo & Jackson, 2013; Carrozzo et al., 2010; Dittrich & Lea, 1994; Gao et al., 2009; Gao & Scholl, 2011; Lee, Gao, & McCarthy, 2012; Lindemann et al., 2011; Meyerhoff, Huff, & Schwan, 2012; Meyerhoff, Schwan, & Huff, 2014; Nairne et al., 2013; Pratt et al., 2010). These studies have successfully demonstrated that motion interactions automatically induce animacy perception. However, semantic information or causality embedded in an interactive motion display is ambiguous as to how visual processing of motion perception modulates animacy perception.

The goal of the present study was to bridge low-level motion perception and animacy perception by excluding semantic information or causality from a motion interaction. More specifically, the goal was to reveal whether motion interaction alone could increase or decrease perceived animacy. For this purpose, although the importance of objective measurements was addressed (Scholl & Gao, 2013), the present study concentrated on measuring subjective reports of animacy rather than measuring objective behavioral performance.[1] The simplest form of motion interaction between several geometric shapes should include coherent or synchronous motion.[2] Coherent motion has attracted attention as a way to reveal mechanisms and neural correlates of global motion perception (Gilaie-Dotan et al., 2013; Nishida, 2011). However, to the best of our knowledge, no study has explored how synchronous motion contributes to these high-level percepts. Recent neuroimaging studies have shown that coherent visual motion induces brain activity outside occipital sites, including the intraparietal sulcus (IPS) and superior temporal sulcus (STS; Braddick et al., 2001). Interestingly, these areas, especially the STS, are also activated by biological motion perception (Blake & Shiffrar, 2007) and animacy perception (Gao, Scholl, & McCarthy, 2012; Osaka, Ikeda, & Osaka, 2012; Schultz, Friston, O'Doherty, Wolpert, & Frith, 2005). Given these findings, the present study hypothesized that synchronous motion might be closely or directly related to high-level percepts; hence, synchronous motion might modulate animacy perception, even without embedding explicit semantic information or causality into the motion.

The present study presented a target dot with several task-irrelevant dots. The dots created random motions in which trajectory was generated based on a variant of 1/f noise. This type of motion can induce animacy perception to some degree (Fukuda & Ueda, 2010). In the present study, participants viewed a stimulus display for 3 s and then rated how strongly they perceived animacy and intention from the target dot. We examined the effects of motion interaction by manipulating the motion of task-irrelevant dots. It is noteworthy that this manipulation makes motion trajectory of the target dot statistically consistent between several experimental conditions.

We also manipulated motion smoothness. Apart from motion interactions between visual objects, the local motion profile (e.g., velocity) of a single visual object can influence high-level percepts (Dittrich & Lea, 1994; Fukai & Terada, 2013; Schultz & Bülthoff, 2013; Tremoulet & Feldman, 2000, 2006). Moreover, coherent motion perception depends on local factors, as well (e.g., contrast, spatial frequency, or speed; Alais, van der Smagt, van den Berg, & van de Grind, 1998). Therefore, examining modulation of a motion interaction against various local motion profiles allows us to untangle this mutual dependence. Since the motion trajectory was based on a variant of the Perlin noise series, motion smoothness could be parametrically manipulated.

Finally, participants were asked to rate perceived intention, as well as perceived animacy. Animacy indicates that something appears to be alive while intention indicates something appears to move in orientation toward a specific (not only physical but also conceptual) goal. Thus, these two percepts are distinguishable; however, they are mutually dependent, are somewhat inseparable, and are potentially confounded. Inspecting both the animacy and intention rating for the same stimulus display likely allows the assertion that participants actually rated perceived animacy. If ratings of animacy and intention qualitatively differ (Fukai & Terada, 2013), this would imply participants used, at least partially, different dimensions for these two ratings.

Experiment 1 investigated the effects of motion interaction and motion smoothness, observing that synchronous motion drastically weakened perceived animacy. Since synchronous motion is a novel factor influencing animacy perception, a series of follow-up experiments further inspected details of this effect by manipulating various characteristics (e.g., spatial separation, Experiment 2; temporal separation, Experiment 3; synchronous magnitude, Experiment 4; motion frequency, Experiment 5). Finally, Experiment 6 also examined whether synchronous changes other than motion could influence animacy perception. Online demonstrations for the present study are available at http://www.fennel.rcast.u-tokyo.ac.jp/research/dot-animacy/.

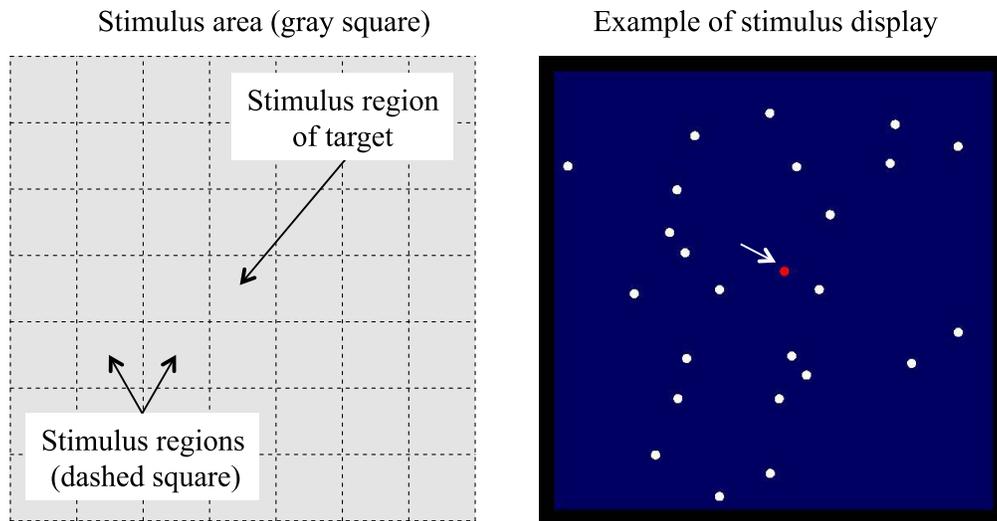Stimulus area (gray square)   Example of stimulus display

Figure 1. Stimulus display. Left: Schematic illustration of the stimulus display. Note that dashed lines were not shown during the experiments. Each dot moved inside one of the stimulus regions. A target dot always appeared in the central region, whereas task-irrelevant dot regions were determined randomly. Right: An example stimulus display. The arrow, which was not presented during the experiments, indicates the target dot.

Experiment 1

Methods

Participants

Thirty volunteers participated after providing written informed consent. All participants had normal or corrected-to-normal visual acuity. The Ethics Committee of the University of Tokyo approved the study in accordance with the Declaration of Helsinki.

Apparatus and stimuli

Experiments were run in a dark and quiet room. The visual stimuli were presented on a CRT monitor (refresh rate was 75 Hz) at a viewing distance of approximately 57 cm. Experiments were conducted on an Apple Mac mini using MATLAB software (MathWorks, Natick, MA) with the Psychophysics Toolbox extension (Brainard, 1997; Kleiner, Brainard, Pelli, Ingling, & Murray, 2007; Pelli, 1997).

Figure 1 depicts an example stimulus display. The visual stimuli were presented at the center of a black screen. A display consisted of a stimulus area and 25 moving dots (diameter of 1°). The stimulus area (15.6° × 15.6°) was on a dark blue background and divided into 7 × 7 imaginary subregions. Each dot moved inside one of 49 nonoverlapping regions. Thus, dots appeared in 25 out of 49 regions; the other regions were empty. Dot motion trajectories followed a variant of the Perlin noise series (Appendix A). The target dot was red and always appeared in the central region so that participants could easily locate the target; this was done to

avoid influences from extraneous factors (e.g., attentional reorienting). The task-irrelevant dots were white, and their regions were randomly determined on each trial.

We manipulated two stimulus factors. The first was motion interaction. During the single condition, only the target dot moved while the other dots remained still. During the independent condition, all dot motion trajectories followed an independently generated noise series. During the synchronous condition, all dot motion trajectories were identical. The semisynchronous condition was the same as the synchronous condition except task-irrelevant dot trajectories were randomly rotated at 0°, 90°, 180°, or 270°. The second factor was motion smoothness, which was controlled by the noise parameter α (see Appendix A). Values for α were 0.95 (least smooth), 1.45, 1.95, or 2.45 (most smooth).

Procedure

Half of the participants were assigned to the animacy task, while the other half were assigned to the intention task. In both tasks, participants were instructed to focus on the target dot and ignore the irrelevant dots. During the animacy task, participants were instructed to rate how strongly they felt the target dot was "alive." During the intention task, participants were instructed to rate how strongly they felt the target dot had "intention."

A trial began by a participant's mouse click. After a 0.2 s blank screen, the stimulus display was presented for 3 s, which was followed by a rating display. Participants rated animacy or intention strength on a 7-
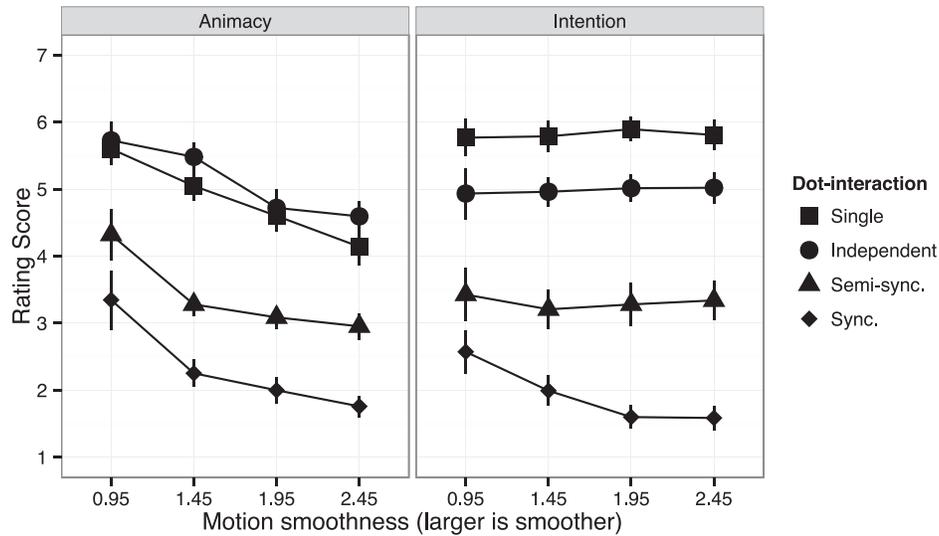
Figure 2. Results of Experiment 1. Error bars indicate *SEM*.

point scale via a mouse click. Participants performed 16 practice trials and 160 experimental trials (4 motion synchrony × 4 motion smoothness × 10 repetition). Each condition was presented in a pseudorandom order.

Results and discussion

Figure 2 shows results of Experiment 1. For the animacy task, significant main effects of motion interaction, $F(3, 42) = 52.1$, $p < 0.001$, $\eta_p^2 = 0.79$, and motion smoothness, $F(3, 42) = 11.4$, $p < 0.01$, $\eta_p^2 = 0.45$, were observed. Pairwise comparisons (corrected for multiple comparisons using Ryan's method) for motion interaction revealed that the animacy rating was highest in the single and independent conditions, followed (in order) by the semisynchronous and synchronous conditions. These results suggested that the presence of synchronous motion weakened the stimulus animacy. Moreover, while the greater magnitudes of synchronization resulted in the stronger reduction of animacy, the presence of asynchronous motion had little effects on the stimulus animacy. Further pairwise comparisons regarding effects of motion smoothness showed that the least smooth motion led to a higher animacy rating than the other conditions.[3] A two-way interaction, $F(9, 126) = 2.14$, $p < 0.05$, $\eta_p^2 = 0.13$, was also observed; however, the effects of motion smoothness were significant for all motion interaction conditions, $F(3, 42) > 6.34$, ps < 0.05, $\eta_p^2 > 0.31$.

For the intention task, the main effect of motion interaction was significant, $F(3, 42) = 68.5$, $p < 0.001$, $\eta_p^2 = 0.83$, while the effect of motion smoothness was not significant, $F(3, 42) = 0.43$, $p = 0.56$, $\eta_p^2 = 0.03$. Pairwise comparisons revealed that intention ratings

were highest for the single condition, followed by the independent, semisynchronous, and synchronous conditions. These results suggested that, unlike animacy, the presence of asynchronous motion would also weaken the intention perception, although the magnitudes of effects were weaker than those of the synchronous motion. A significant two-way interaction, $F(9, 126) = 2.75$, $p < 0.05$, $\eta_p^2 = 0.16$, also emerged, which suggested that the effects of motion smoothness depended on the motion interaction condition. Motion smoothness was not significant in the single, independent, and semi-synchronous conditions, $F(3, 42) < 0.15$, ps > 0.79, $\eta_p^2 < 0.01$, whereas less smooth motion led to higher intention ratings during the synchronous condition, $F(3, 42) = 5.02$, $p < 0.05$, $\eta_p^2 = 0.26$.[4]

In Experiment 1, using simple noise motion and synchronous motion stimuli, results revealed that (a) synchronous motion strongly modulated animacy and intention perception, and (b) motion smoothness differentially affected these percepts.

Experiment 2: Spatial separation

Given the novel findings observed related to synchronous motion, Experiment 2 attempted to replicate the basic results from Experiment 1 and explore various factors potentially influencing modulation via synchronous motion. In Experiment 1, the target dot was embedded inside the other dots; thus, modulation might have arisen solely from the local motion interaction around the target dot. To test the effects of spatial proximity, Experiment 2 introduced another factor—spatial separation between the target dot and task-irrelevant dots—in the stimulus display.
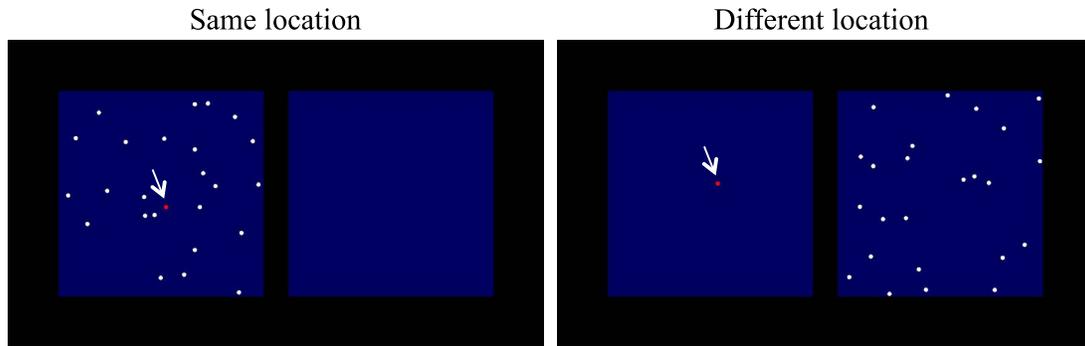
Figure 3. Example stimulus displays in Experiment 2. Left: same location condition. Right: different location condition. The arrow (which was not presented during the experiment) indicates the target dot.

Furthermore, for Experiments 2, 3, 4, 5, and 6, participants engaged in both animacy and intention tasks.

Methods

Thirty volunteers were newly recruited. The methods were similar to Experiment 1 except for the following modifications. All participants performed both the animacy and intention task during separate sessions. Session order was counterbalanced across participants. Only two motion smoothness conditions were presented: least ($\alpha = 0.95$) and most ($\alpha = 2.25$) smooth motion. Two stimulus areas were presented on a display, one of which appeared on the left side, and the other appeared on the right side of the screen (Figure 3). The target dot appeared in the central region in either the left or the right area, which was randomly determined on each trial. Task irrelevant dots were presented in the same stimulus area (same location condition) or the opposite stimulus area (different location condition) as the target dot. During each session, participants performed eight practice trials and 128 experimental trials (4 motion synchrony × 2 motion smoothness × 8 repetition).

Results and discussion

Results are shown in Figure 4. For the animacy task, a three-way repeated-measures ANOVA revealed significant effects of motion interaction, $F(3, 87) = 73.7$, $p < 0.001$, $\eta_p^2 = 0.72$, and motion smoothness, $F(1, 29) = 19.6$, $p < 0.001$, $\eta_p^2 = 0.40$, which replicated results from Experiment 1; however, there was no main effect of location, $F(1, 29) = 1.45$, $p = 0.24$, $\eta_p^2 = 0.05$. Significant two-way interactions between location and motion interaction, $F(3, 87) = 22.4$, $p < 0.001$, $\eta_p^2 = 0.44$, and location and motion smoothness, $F(1, 29) = 5.28$, $p < 0.05$, $\eta_p^2 = 0.15$, also emerged. This indicated that, although effects of

motion interaction were qualitatively similar between the same and different location conditions, the magnitude of the effects depended on spatial proximity. Modulation via synchronous motion of spatially separated dots was slightly weaker than for immediately surrounding dots.

For the intention task, a significant main effect of motion interaction, $F(3, 87) = 27.33$, $p < 0.001$, $\eta_p^2 = 0.48$, was observed, whereas the effect of motion smoothness was not significant, $F(1, 29) = 0.01$, $p = 0.92$, $\eta_p^2 = 0.00$. Pairwise comparisons between the single and independent conditions did not reach significance in Experiment 2. A significant interaction between motion interaction and motion smoothness, $F(3, 87) = 3.69$, $p < 0.05$, $\eta_p^2 = 0.11$, also emerged; however, the effect of motion smoothness was not significant for all types of motion interaction. An analysis involving the location factor suggested the effects of location were significant but subtle. The main effect was not significant, $F(1, 29) = 0.33$, $p = 0.57$, $\eta_p^2 = 0.01$, and only the interaction between location and motion interaction was significant, $F(3, 87) = 12.00$, $p < 0.001$, $\eta_p^2 = 0.29$, which suggested that the effect of motion interaction was slightly weaker in the different location conditions. Note the odd observation at a smoothness = 0.95 in the same location, independent condition. Given a sufficient number of participants, and the robust and stable results outside of this finding, this result is unlikely due to measurement noise. While such an observation is intriguing in terms of intention-from-motion perception, this result will not be mentioned further as it is beyond the scope of the present study.

Experiment 2 successfully replicated the major findings from Experiment 1. Furthermore, the manipulation of spatial location revealed that perceived animacy and intention were effectively weakened, even by the synchronous motion of the spatially separate dots. These results implied that global, rather than local, motion processes were primarily responsible for modulation via motion synchrony. However, at the
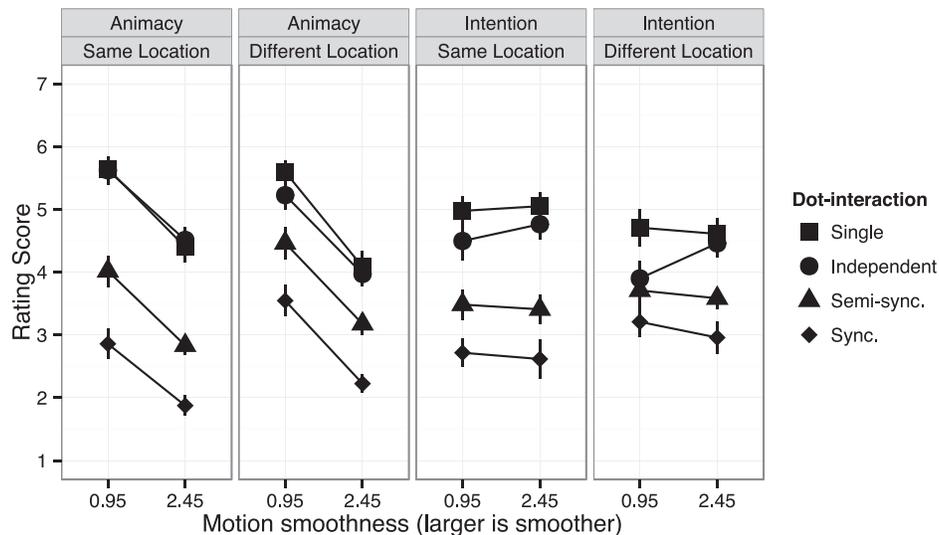
Figure 4. Results of Experiment 2. Error bars indicate *SEM*.

same time, a slight dependency regarding spatial separation was also observed. This may be due to weak dependency regarding spatial distance during synchronous motion detection (Maruya, Holcombe, & Nishida, 2013).

Experiment 3

Experiment 3 introduced a temporal gap between the target dot and other dots. The first purpose of this experiment was to determine the temporal window at which synchronous motion could modulate animacy perception. Furthermore, results from the first two experiments could not exclude the possibility that synchronous motion among task-irrelevant dots, instead of synchronous motion between the target and irrelevant dots, might modulate animacy perception. If a temporal gap nullifies modulation of animacy perception, synchronous motion between the target and irrelevant dots should modulate animacy perception.

Methods

Eighteen volunteers were newly recruited. The methods were similar to Experiment 1 except for the following modifications. All participants performed both the animacy and intention task during separate sessions. The session order was counterbalanced across participants. Only two motion smoothness conditions were presented: least ($\alpha = 0.95$) and most ($\alpha = 2.25$) smooth motion. Motion interaction was either independent or synchronous, while the single and semi-synchronous conditions were removed. A temporal gap

between the target dot and task-irrelevant dots was also introduced. The gap was -250, -100, 0, 100, or 250 ms. The negative gap indicates the target dot preceded the irrelevant dots, while the positive gap indicates the target dot followed irrelevant dots. During each session, participants performed eight practice trials and 120 experimental trials (2 motion synchrony $\times$ 2 motion smoothness $\times$ 5 delay $\times$ 6 repetition).

Results and discussion

Figure 5 shows results of Experiment 3. For the animacy task, the effects of motion interaction and motion smoothness replicated the previous experiments. A three-way repeated-measures ANOVA revealed that the independent condition led to a higher animacy rating than the synchronous condition, $F(1, 17) = 28.6$, $p < 0.001$, $\eta_p^2 = 0.63$, and the less smooth motion also led to a higher animacy rating, $F(1, 17) = 4.50$, $p < 0.05$, $\eta_p^2 = 0.21$. Furthermore, the three-way interaction was significant, $F(3, 52) = 3.87$, $p < 0.05$, $\eta_p^2 = 0.17$, in which motion interaction was significant only at the 0-ms gap during the less smooth condition and at 0-, 100-, and 250-ms gaps in the smoother conditions.

For the intention task, the main effect of smoothness was not significant, $F(1, 17) = 0.05$, $p = 0.82$, $\eta_p^2 = 0.00$. The main effect of motion interaction was also nonsignificant, $F(1, 17) = 0.16$, $p = 0.69$, $\eta_p^2 = 0.01$, while the two-way interaction between temporal gap and motion interaction was significant, $F(4, 68) = 17.4$, $p < 0.001$, $\eta_p^2 = 0.51$. Further inspection revealed that motion interaction was significant only during the 0-ms gap condition.

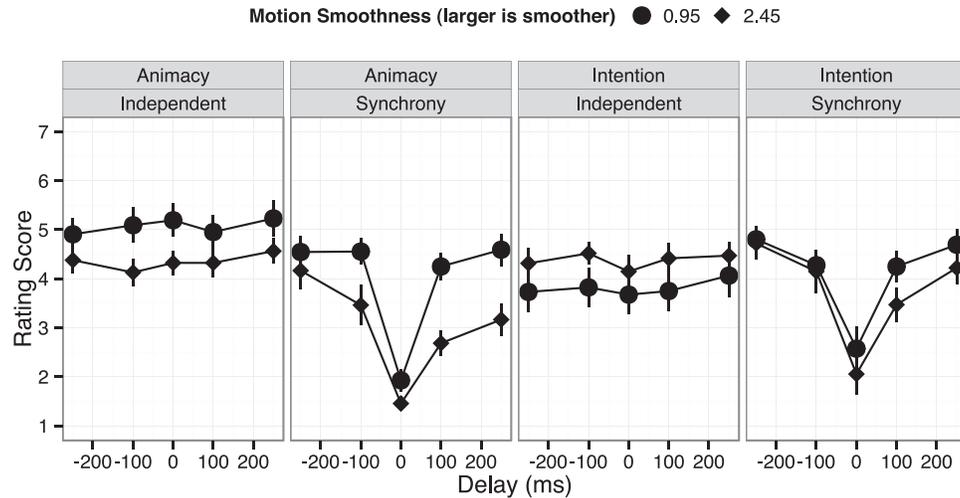**Motion Smoothness (larger is smoother)** ● 0.95 ◆ 2.45

Figure 5. Results of Experiment 3. Error bars indicate *SEM*.

These results demonstrated that a temporal gap nearly nullified the effects of motion interaction. While synchronous motion weakens animacy and intention perception at a 0-ms gap, a temporal gap of only 100 ms drastically reduced the effect. These results implied that (a) the synchronous motion between the target and other dots, rather than among the other dots, is crucial for modulation, and (b) the temporal window of this modulation was quite narrow.

Experiment 4

For the experiments thus far, only synchronous motion of all the dots was examined. However, the visual system is also sensitive to motion coherency. In fact, our visual system is able to detect relatively weak coherence signals in which only a small portion of dots move coherently while other dots move at random (Nishida, 2011; Pilly & Seitz, 2009). It is unclear whether the magnitude of synchronous motion, namely the number of dots producing synchronous motion, influences modulation. Therefore, Experiment 4 manipulated the number of task-irrelevant dots that created synchronous motion with the target.

Methods

Thirty volunteers were newly recruited. Methods were similar to Experiment 3 except for the following modifications. In this experiment, the number of moving dots was manipulated while the temporal gap was removed. The number of moving dots was 1 (only the target dot moved), 4, 9, 16, or 25. The target dot always moved, while a portion of the task-irrelevant dots stood still during the stimulus period. During each session,

participants performed eight practice trials and 120 experimental trials (2 motion synchrony × 2 motion smoothness × 5 number of moving dots × 6 repetitions).

Results and discussion

Figure 6 shows results from Experiment 4. For the animacy task, a three-way repeated-measures ANOVA revealed significant main effects of motion interaction, $F(1, 29) = 124.3$, $p < 0.001$, $\eta_p^2 = 0.81$, and motion smoothness, $F(1, 29) = 6.17$, $p < 0.05$, $\eta_p^2 = 0.18$, which replicated results from the previous experiments. Furthermore, a two-way interaction between the number of moving dots and motion interaction, $F(4, 116) = 81.2$, $p < 0.001$, $\eta_p^2 = 0.74$, emerged. Further inspection indicated that the effect of moving dot number was qualitatively different between the independent and synchronous conditions. In the independent condition, a larger number of moving dots slightly strengthened perceived animacy, $F(4, 116) = 6.16$, $p < 0.001$, $\eta_p^2 = 0.18$; pairwise comparisons, $1 < 16$, $1 < 25$, and $4 < 25$. Conversely, in the synchronous condition, a larger number of moving dots rapidly and drastically weakened perceived animacy, $F(4, 116) = 44.7$, $p < 0.001$, $\eta_p^2 = 0.61$; pairwise comparisons: $1 >$ others, $4 > 16$ and 25, and $9 > 25$. A multiple linear regression analysis was also performed for the synchronous condition using data from the 4, 9, 16, and 25 dots conditions, which revealed a significant slope (−0.15/dot, $t = 3.18$, $p < 0.01$).

For the intention task, a significant main effect of motion interaction emerged, $F(1, 29) = 27.1$, $p < 0.001$, $\eta_p^2 = 0.48$, but there was no effect of motion smoothness, $F(1, 29) = 0.94$, $p = 0.34$, $\eta_p^2 = 0.03$, which, again, replicated results from the previous experiments. A two-way interaction between the number of moving dots and motion interaction, $F(4, 116) = 17.1$, $p < 0.001$, $\eta_p^2 =$
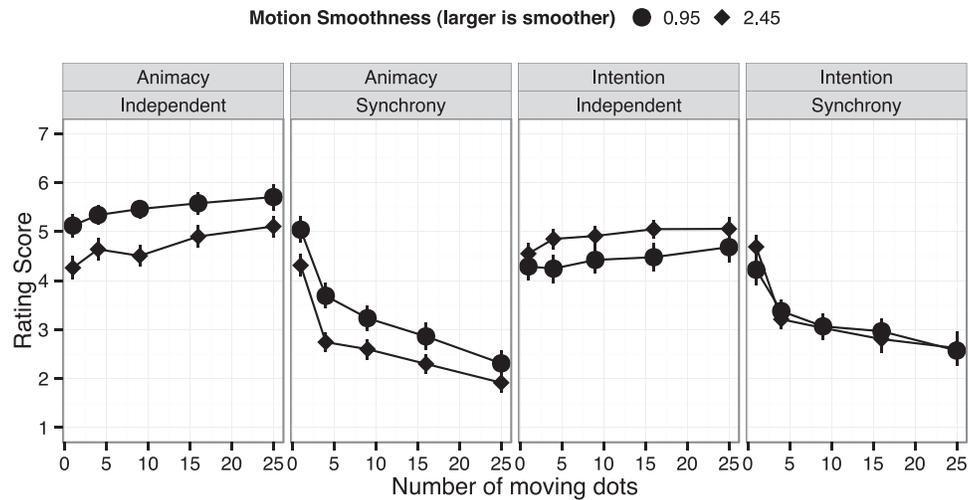
Figure 6. Results of Experiment 4. Error bars indicate *SEM*.

0.37, was also revealed. The number of dots differentially influenced intention perception between the independent and synchronous conditions. In the independent condition, a larger number of moving dots slightly strengthened perceived intention, $F(4, 116) = 3.55$, $p < 0.05$, $\eta_p^2 = 0.11$; pairwise comparisons: $1 < 25$, whereas in the synchronous condition, a larger number of moving dots rapidly and drastically weakened perceived intention, $F(4, 116) = 13.7$, $p < 0.001$, $\eta_p^2 = 0.32$, pairwise comparisons: $1 > $ others. However, the number of dots did not significantly influence perceived intention within the 4-, 9-, 16-, and 25-dot conditions. A regression analysis revealed only a marginally significant slope (-0.008/dots, $t = 1.86$, $p = 0.063$). The influence of synchronous motion magnitude for the intention rating was even weaker than for the animacy rating.

These results demonstrated that synchronous motion within a small portion of dots sufficiently weakened perceived animacy and intention. Furthermore, the effect of dot number in the synchronous condition was even stronger during the animacy perception task than during the intention perception tasks. In short, animacy perception tended to quantitatively reflect the number of synchronously moving dots.

Experiment 5

For all experiments up until this point, local trajectories of the target and irrelevant dots were identical in the synchronous condition. The Perlin noise series contains a wide range of frequencies, and dot movement consists of a slow and large (i.e., low frequency) movement and a fast and small (i.e., high frequency) movement. It is unclear whether the low frequency component or the high frequency component plays a more significant role in animacy perception. It is

possible that complete synchrony could be necessary for modulating animacy perception. Thus, Experiment 5 applied a low-pass or a high-pass filter to the motion trajectory of task-irrelevant dots.

Methods

Seventeen volunteers were newly recruited. Methods were similar to Experiment 1. Motion smoothness was set to 0.95, 1.10, 1.25, or 1.40.[5] As for motion interaction, the independent condition and synchronous conditions were identical to those in Experiment 1. The low-pass and high-pass conditions were the same as the synchronous condition except that the respective filter was applied to the trajectory of task-irrelevant dots, respectively. A cutoff frequency of 3.75 Hz (¹⁄₁₀ of the Nyquist frequency) was used. In the low-pass condition, the target and task-irrelevant dots shared the slow and large movement while fast and small movement was removed from task-irrelevant dots. In the high-pass condition, dots shared the fast and small movement while the slow and large movement was removed. During each session, participants performed eight practice trials and 128 experimental trials (4 motion synchrony × 4 motion smoothness × 8 repetition).

Results and discussion

Figure 7 shows results of Experiment 5. For the animacy task, a two-way repeated-measures ANOVA revealed a significant main effect of motion interaction, $F(3, 48) = 96.0$, $p < 0.001$, $\eta_p^2 = 0.96$, and a significant interaction, $F(9, 144) = 10.74$, $p < 0.001$, $\eta_p^2 = 0.40$, while the main effect of motion smoothness did not reach
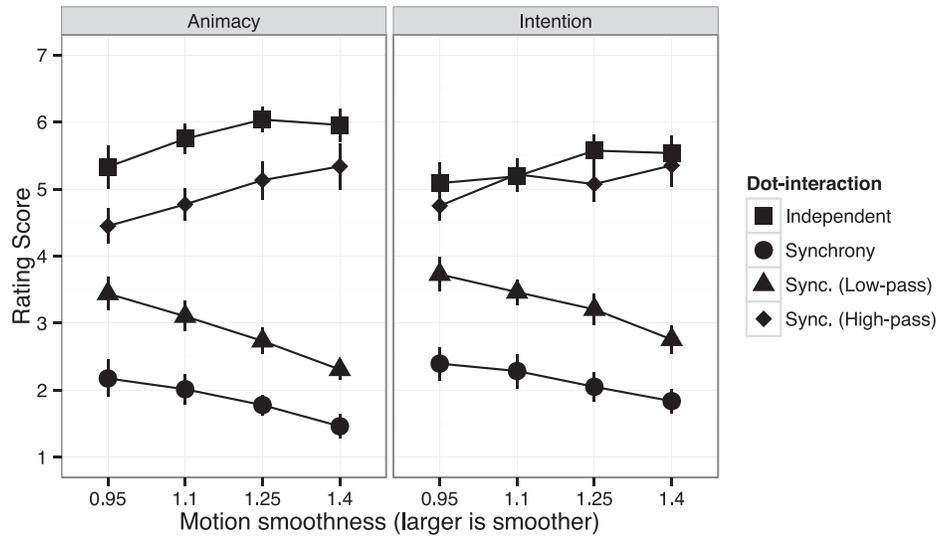
Figure 7. Results of Experiment 5. Error bars indicate *SEM*.

significance, $F(3, 48) = 0.51$, $p = 0.53$, $\eta_p^2 = 0.03$. Pairwise comparisons indicated that perceived animacy was stronger in the independent, high-pass, low-pass, and synchronous conditions (in that order) regardless of motion smoothness. The effects of motion smoothness depended on motion interaction. Smoother motion led to stronger animacy in the independent and high-pass conditions, while smoother motion led to weaker animacy in the low-pass and synchronous conditions. Another interesting observation was that modulation (i.e., a decrease from the independent condition) in the synchronous condition (mean = 3.91) was almost equal to the sum of modulations (mean = 3.71) in the high-pass (mean = 0.85) and low-pass (mean = 2.97) conditions, $t(16) = 0.51$, $p = 0.61$. These results suggest that effects of the high-frequency and low-frequency components might be independent and additive.

For the intention task, a significant main effect of motion interaction, $F(3, 48) = 72.0$, $p < 0.001$, $\eta_p^2 = 0.82$, and a significant interaction emerged, $F(9, 144) = 6.88$, $p < 0.001$, $\eta_p^2 = 0.30$, but no effect of motion smoothness was observed, $F(3, 48) = 0.37$, $p = 0.64$, $\eta_p^2 = 0.02$. Perceived intention was comparable between the independent and high-pass conditions, which were stronger than the low-pass condition. The synchronous conditions led to weaker intention as compared to the other conditions. The effect of motion smoothness depended on motion interaction. The effect of smoothness was not significant in the independent and high-pass conditions, while smoother motion led to weaker perceived intention in the low-pass and synchronous conditions. Furthermore, unlike the animacy task, modulation in the synchronous condition (mean = 3.20) was not equal to but larger than the sum of the modulations (mean = 2.30) in the high-pass (mean = 0.24) and low-pass (mean = 2.06) conditions,

$t(16) = 2.93$, $p < 0.01$. These results suggest that the high-frequency component modulated intention perception only when the low-frequency component was synchronous.

Experiment 5 suggested that low-frequency motion had greater effects on the modulation of animacy and intention perception. Furthermore, the effects of high-frequency motion differed between these two percepts.

Experiment 6

Experiments 1, 2, 3, 4, and 5 demonstrated robust and strong modulations of animacy perception through synchronous motion. However, motion is not the only visual feature that creates synchrony. Various visual features other than motion (position), such as luminance, color, size, or tilt, could synchronously change. It is still unclear whether synchronous changes of visual features other than motion affect animacy perception. Thus, Experiment 6 investigated the effects of synchronous changes in luminance (Experiment 6A) and size (Experiment 6B). Note that the target kept moving and an additional modulation of size and color was added. This was done in lieu of making the target static and examining the modulation of synchronous size and color changes, since static dots cannot appear to be animate.

Methods

Fourteen and 15 volunteers were newly recruited for Experiments 6A and 6B, respectively. Methods were similar to Experiment 1. Motion smoothness was set to 0.95 or 2.25. The motion interaction condition was
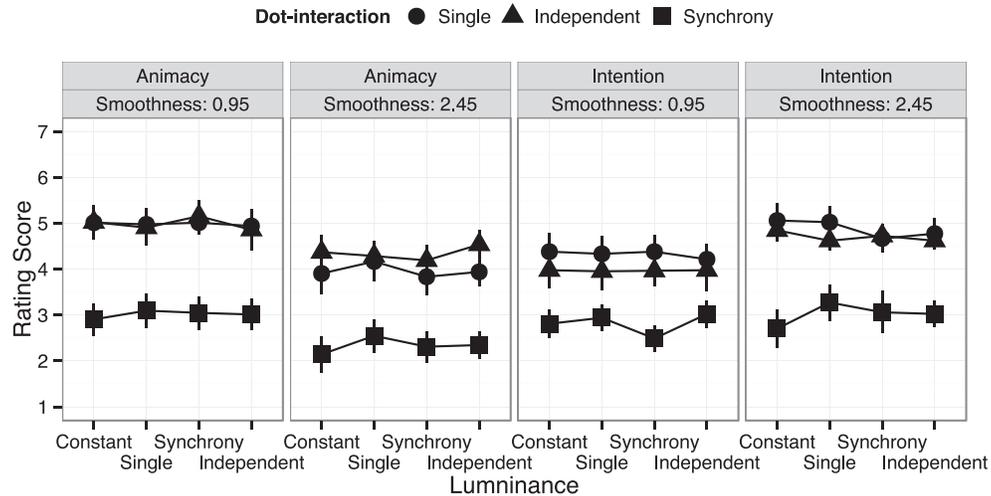
Figure 8. Results of Experiment 6A. Error bars indicate *SEM*. The horizontal axis indicates the luminance change condition, and different smoothness appears in separate panels.

single, independent, or synchronous. A new factor was introduced, namely changes to dot luminance (Experiment 6A) and size (Experiment 6B). There were four conditions with these factors: constant, single, synchronous, and independent. In the constant condition, dots did not change their luminance or size. In the single condition, only the target dot changed its luminance or size at a frequency of 1–2 Hz. In the synchronous condition, all dots synchronously changed their luminance or size at a frequency of 1–2 Hz. In the independent condition, all dots changed their luminance or size, while the frequency and phase were randomly determined for each dot. During each session, participants performed eight practice trials and 144 experimental trials (3 motion synchrony × 2 motion smoothness × 4 change type × 6 repetition).

Results and discussion

Experiment 6A

Figure 8 shows results of Experiment 6A. For the animacy task, a three-way repeated-measures ANOVA revealed a significant main effect of motion interaction, $F(2, 26) = 32.4$, $p < 0.001$, $\eta_p^2 = 0.71$, while the other main effects and interactions did not reach significance, $Fs < 2.17$, $ps > 0.17$, $\eta_p^2 < 0.15$. As was revealed in the previous experiments, synchronous motion drastically weakened perceived animacy compared with a single and independent motion. However, in contrast to synchronous motion, a synchronous change in luminance did not affect animacy perception.

For the intention task, only a significant main effect of motion interaction, $F(2, 26) = 9.28$, $p = 0.004$, $\eta_p^2 = 0.42$, was observed. Again, synchronous motion weakened perceived intention, while changes in syn-

chronous luminance did not affect intention perception.

Experiment 6B

Figure 9 shows results of Experiment 6B. For the animacy task, a three-way repeated-measures ANOVA revealed that all main effects and two-way interactions were significant. In general, previous results were replicated; that is, synchronous motion weakened perceived animacy, $F(2, 28) = 29.4$, $p < 0.001$, $\eta_p^2 = 0.68$, and smoother motion weakened perceived animacy, $F(1, 14) = 19.7$, $p = 0.001$, $\eta_p^2 = 0.59$. An effect of size change, $F(3, 42) = 3.36$, $p = 0.03$, $\eta_p^2 = 0.19$, was also observed. However, pairwise comparisons revealed that the constant condition led to weaker animacy as compared to the other conditions. Thus, perceived animacy was slightly strengthened when the target dot changed its size; importantly, the synchronous change in size did not weaken perceived animacy. It is noteworthy that the effect of size change was significant only when the dot had relatively weak animacy (i.e., a synchronous motion condition with a motion smoothness of 2.45), which suggests size change strengthened the perceived animacy of objects inherently perceived as weakly animate.

For the intention task, significant main effects of size change, $F(3, 42) = 7.64$, $p = 0.001$, $\eta_p^2 = 0.35$, and motion interaction, $F(2, 28) = 15.0$, $p < 0.001$, $\eta_p^2 = 0.52$, emerged, while the other main effects and interactions did not reach significance, all $Fs < 2.21$, $ps > 0.07$, $\eta_p^2 < 0.14$. Further inspection of the size change effect revealed that the constant condition led to weaker perceived intention as compared to the other conditions.
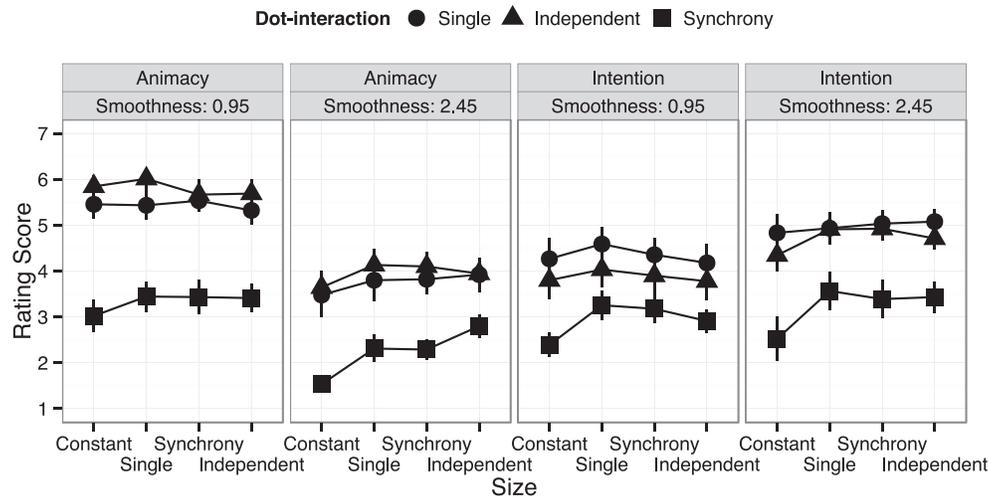
Figure 9. Results of Experiment 6B. Error bars indicate *SEM*. The horizontal axis indicates the size change condition, and different smoothness appears in separate panels.

Results from Experiment 6A and 6B clearly demonstrated synchronous changes other than location (i.e., synchronous motion) did not modulate the animacy and intention percepts.

General discussion

Visual motion provides more than an object's spatiotemporal dynamics. Motion can serve as a cue for high-level percepts such as material transparency (Kawabe et al., 2014), biological features (Johansson, 1973), intention, causality, and animacy (Scholl & Tremoulet, 2000). The present study extended this research by demonstrating strong modulation of animacy perception via motion, especially motion interaction. The basic finding was that perceived animacy from a target dot was drastically weakened by the presence of dots in synchronous motion with the target dot; otherwise, strong animacy perception emerged from the target dot.

Interactive motion between two or more objects is known to induce animacy perception. However, in most cases, this motion interaction explicitly indicates semantic information or causality, as seen in Heider and Simmel's (1944) animation, Michotte's (1963) animation, and chasing experiments (Dittrich & Lea, 1994; Gao et al., 2009; Gao & Scholl, 2011; Lee et al., 2012; Meyerhoff et al., 2012; 2014). In contrast, the present study tested the simplest form of motion interaction—synchronous motion—that was not designed to embed any specific semantic information or causality during motion interaction. Using this type of motion, robust modulation of animacy perception via synchronous motion was revealed.

Before discussing the details regarding synchronous motion modulation, it is important to address issues relevant to the entity of animacy perception in the present and previous studies. Traditionally, visual stimuli used in animacy studies are designed so that the stimuli provide social or semantic interaction; hence, the stimuli appear to be more or less a "social" agent (e.g., Heider and Simmel's animation [1944] or the "wolfpack effect"). Conversely, the present study intended to exclude these kinds of social or semantic features from the visual stimuli, following recent studies testing spatiotemporal patterns of simple motion trajectories (e.g., Dittrich & Lea, 1994; Fukai & Terada, 2013; Schultz & Bülthoff, 2013; Tremoulet & Feldman, 2000, 2006). While these animacy studies use the term "animacy" for both cases, it is open to debate whether the qualitative entity of animacy perception is the same or different between these two types of stimuli (i.e., "social animacy" vs. "kinematic animacy"). Therefore, implications of the present findings are limited to the latter case. Nevertheless, it is clear that animate objects are not necessarily social agents, since animacy does emerge in the absence of social agency (e.g., 1/f motion). Although this issue is beyond the scope of the present study, differentiating and comparing kinematic and social animacy would be a promising and intriguing direction for better understanding animacy perception.

Spatial and temporal separation

Experiment 2 showed that synchronous motion of task-irrelevant dots modulated target animacy, even when the target and irrelevant dots were spatially apart from each other. This suggested that synchronous motion interacted with animacy perception within a

wide field of view. Conversely, spatial separation slightly reduced modulation elicited by synchronous motion. Synchronous motion detection is fast and surprisingly robust within a large field of view; however, detectability slightly depends upon the spatial separation between targets (Maruya et al., 2013). Hence, it is not the modulation on animacy perception per se but synchronous motion detection that would likely be responsible for the slight reduction in modulation via synchronous motion in Experiment 2.

In contrast, Experiment 3 showed a slight temporal gap between target dot motion and task-irrelevant dot motion, which nearly nullified this modulation. This result rules out the possibility that participants' inferences of a target's animacy would be weak since the target had a similar motion trajectory to the other dots. The effects of a temporal gap highlight the importance of perceptual motion coherency between the target and other dots. Experiment 3 provided another important implication; rather than synchronous motion among task-irrelevant dots, synchrony between the target and other dots was what modulated target animacy. In other words, the presence of synchronous motion in the visual field alone could not modulate animacy perception. Thus, perceived animacy of an object is likely weakened when, and only when, an object creates synchronous motion with other objects.

Low and high frequency synchronous motion

Unlike typical coherent motion, motion trajectories in the present study were a variant of 1/f noise and contained a wide range of temporal frequency components. In Experiment 5, low-pass and high-pass temporal filters were applied to the motion trajectory of task-irrelevant dots. Note that trajectory of the target dot was statistically consistent across all conditions. Modulation was strongest during complete synchronous motion, and modulation by low-pass filtered synchronous motion was much stronger than high-pass filtered synchronous motion. This result suggests that the large and slow component might be influential for this modulation. However, the small and fast component was not negligible; interestingly, modulation by complete synchrony was almost equal to the sum of modulations using low-pass and high-pass filters. This result suggests that two independent mechanisms might underlie modulation of animacy perception, and these two mechanisms additively contributed to this modulation.

Binding versus synchronous motion

Synchronous change of visual features is supposed to facilitate binding or feature integration among multiple visual objects (Cheadle et al., 2008; Gray, 1999; Singer & Gray, 1995; Usher & Donnelly, 1998). Therefore, in the present study, target dots were likely bound to task-irrelevant dots that moved in sync. The binding process might have been what played a crucial role during animacy perception. If this were the case, synchronous changes of any visual feature other than motion would also modulate animacy perception. However, Experiment 6 demonstrated that synchronous changes in luminance or size did not weaken perceived target animacy; thus, the binding process unlikely served as a modulator of animacy perception. It is noteworthy that these results do not necessarily rule out the possibility that synchronous changes of visual features other than motion could influence animacy perception. In Experiment 6, the effects of synchronous size/color changes on animacy-from-motion were tested by keeping the target dot moving. This stimulus configuration might have facilitated motion salience, while size/color changes were simply ignored. Furthermore, size and/or color changes might have influenced animacy from nonmotion features (e.g., animacy from appearance, animacy of face, etc.). Overall, it appears that synchronous motion has a special role in animacy-from-motion perception. It is an open question as to whether animacy from visual features other than motion is susceptible to the synchronous changes of nonmotion features.

Global surface versus synchronous motion

Synchronous motion of the whole stimulus display likely induced perception of a global moving surface that included a specific number of dots. Thus, which portion of the synchronous motion or perception of a global surface was primarily responsible for reduction in animacy? In Experiment 4, the number of dots that created synchronous motion was manipulated, which suggested that only three dots in sync with the target weakened perceived target animacy. These results are consistent with superior sensitivity to coherent motion; a low motion coherence of around 5% is detectable (Nishida, 2011; Pilly & Seitz, 2009), and perceptual learning takes place even without awareness of coherent motion (Watanabe, Náñez, & Sasaki, 2001). Results of Experiment 2 showed that synchronous motion with dots in a spatially separate visual field modulated target animacy, whereby the global surface would not be clearly perceived. In Experiment 5, it was also demonstrated that low-pass filtered motion elicited animacy reduction. These observations may favor the conclusion that synchronous motion per se was the primary factor. However, the effects of global surface perception cannot be completely ruled out since global surface perception may appear even

for a small number of dots in sync. This could even be the case for spatially separated dots that are in sync and for dots in sync at a low-frequency component. Thus, it is still unclear whether surface perception is a primary factor for animacy reduction. However, in Experiment 5, a reduction in animacy for high-pass filtered motion was observed (independent condition vs. high-pass synchronous condition). It would be reasonable to assume that no global surface appeared for this stimulus display. Therefore, this result suggests that synchronous motion modulates animacy perception to some extent, regardless of global surface perception.

Motion smoothness and motion interaction

While the present study focused on modulation through motion interaction, motion smoothness was also manipulated. Robust effects regarding animacy perception were revealed wherein less smooth motion strengthened perceived animacy (except for Experiment 5, in which the range of motion smoothness was quite narrow). It is plausible that an individual dot's dynamic movement expresses the dot as vigorously "alive." Importantly, motion smoothness did not interact with modulation via motion interaction. Perhaps animacy perception is a complex array of various visual cues (e.g., individual motion, motion interaction, semantic information, causality, etc.). The present study underscores the fact that individual motion profiles and global synchronous motion independently and additively contributes to animacy perception. Since the current study concentrated on an extremely simplified situation, it has yet to be determined whether this additive and independent rule can be applied to every combination of several visual features.

Although the effects of motion smoothness were robust in the present study, how this effect can be generalized needs to be determined. The current study used simple dot motion of a 1/f noise variant to exclude semantic information and, at the same time, facilitate animacy perception. Animacy perception induced by 1/f noise motion might be qualitatively different from a motion interaction with semantic information or causality. To better understand the totality of animacy perception, it would be interesting to examine the effects of motion smoothness, or the effects of individual object motion dynamics, with a semantic motion interaction display similar to animations by Heider and Simmel (1944) and Michotte (1963), or a chasing paradigm (Dittrich & Lea, 1994; Gao et al., 2009; Gao & Scholl, 2011; Lee et al., 2012; Meyerhoff et al., 2012; 2014).

Similarity and dissimilarity between animacy and intention

Disentangling animacy perception from intention perception is not an easy task (Scholl & Gao, 2013; Scholl & Tremoulet, 2000); however, some studies have shown a qualitative dissociation between the two (Fukai & Terada, 2013; Gao et al., 2012). The present study found that certain factors differentially influenced animacy and intention perception. First, in contrast to animacy perception, where a less smooth motion led to stronger perceived animacy, the effects of motion smoothness on intention perception were almost negligible. Second, in Experiment 5, high-pass filtered synchronous motion did not weaken perceived intention; however, it did significantly weaken perceived animacy. Importantly, this qualitative dissociation between animacy and intention perception confirmed that participants indeed rated animacy and intention on different dimensions, even with a partial overlap.

Perceived intention should be mainly determined by slow and large motion: in other words, the low-pass filtered motion trajectory. Conversely, a wider frequency range, including fast and slow motion, should determine perceived animacy. This might be reasonable considering the nature of animacy and intention; the high-pass filtered fast and small motion corresponds to the bodily movement of an animate object, while the low-pass filtered slow and large motion corresponds to object locomotion. Intention perception seems to be mainly associated with locomotion, while animacy is associated more with individual bodily movement. This distinction between locomotion and bodily movement warrants further investigation.

High-level cognition and low-level perception

The current study only used subjective ratings of animacy and intention as a dependent variable. This is because, unlike semantic displays such as Heider and Simmel's (1944) animation, the relationship between synchronous motion and animacy perception was completely unknown. Thus, a subjective rating experiment was an appropriate starting point. Although this approach is widely used in other animacy studies (Scholl & Tremoulet, 2000; Tremoulet & Feldman, 2000, 2006), this approach cannot be used to conclude which of the lower-level perceptual processes or higher-level cognitive inferences or reasonings (or both) mediated modulation via synchronous motion. Recently, this issue was elaborately discussed (Scholl & Gao, 2013), and Gao and colleagues adopted a strategy that associates objective measurements, such as attentional modulation or avoidance behavior, with animacy

perception (Gao et al., 2009; 2010; Gao & Scholl, 2011). Thus, whereas the present study demonstrated the robust and strong modulations from synchronous motion, extensive studies are needed to reveal that low-level perceptual processes are involved in the animacy-from-motion perception, especially by using objective measurements and by associating with behavioral effects rather than subjective reports. The visual stimuli used in the present study are viable for investigating these issues, since the modulations were robust and strong, and the absence of any semantic features in the stimulus display allowed for a quantitative manipulation of the visual stimuli (e.g., sync rate or spatial/temporal separation).

Why does synchronous motion weaken animacy?

Why does synchronous motion weaken animacy? At the moment, there is no conclusive explanation; however, a few possibilities are available. The first possibility is based on higher-level modulation related to the individualization of a target. In the independent condition, since target motion was independent from, and unrelated to, the other dots' motion, the target appeared to be an individualized object. Conversely, in the synchronous condition, the target dot appears as if it is a part of something (e.g., rigid surface or rigid body). Thus, the target is not an individualized object anymore; rather, the target is an element of the object. Any part of an object, alone, may not efficiently elicit animacy perception, given that any single part of an object cannot be an animate individual.

The second possibility is related to perceptual causality and animacy (Scholl & Tremoulet, 2000). In general, an object's motion is driven by either an internal or an external force. Several studies have suggested that motion driven by an internal force, which indicates a violation of Newtonian laws, elicits stronger animacy perception (Scholl & Tremoulet, 2000, Tremoulet & Feldman, 2000, 2006). In the present case, while motion of the target dot was statistically consistent between all conditions, the presence of synchronous motion might imply the presence of a "force field"; thus, observers may have attributed the cause of a target's motion to be an external force field without violating Newtonian laws rather than an internal force inside the target.

The third possibility is based on low-level modulations of motion perception. Motion perception per se is strongly influenced by background motion. For example, the freezing rotation illusion (Dürsteler, 2008) demonstrates that perceived motion velocity is drastically reduced by the presence of background patterns moving towards the same direction. In an analogous way,

perceived motion "randomness" may be reduced by the presence of background patterns moving in sync. If this is the case, assuming that the randomness of 1/f motion is important for animacy-from-motion, motion perceived as lower in randomness may not meet the condition necessary for eliciting animacy perception. These aforementioned possibilities are not mutually exclusive. Since the processes underlying animacy perception appear to be quite complicated, animacy reduction likely also involves a variety of other processes.

Conclusion

The present study revealed certain effects of synchronous motion on high-level perception. Synchronous motion is a strong modulator of animacy perception. The perceived animacy of an object is drastically weakened when the object moves synchronously with other objects. Unlike previous animacy-from-motion studies, synchronous motion does not embed any semantic information; nevertheless, synchronous motion can modulate animacy perception. During the emergence of high-level motion percepts, a bottom-up pathway might play a more important role than was previously thought. Although the underlying neural mechanisms remain to be known, STS likely deals with the crossover between motion processing and animacy perception, given that coherent motion leads to STS activation (Braddick et al., 2001); the STS is also activated by animacy perception (Gao et al., 2012; Osaka et al., 2012; Schultz et al., 2005). The effects of synchronous motion are rather strong, as it is easy to quantitatively manipulate visual stimulus characteristics. Thus, future studies should continue assessing animacy perception using synchronous motion stimuli.

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Footnotes

[1] In the General discussion, we discussed further the issue regarding objective measurements versus subjective reports (see section, High-level cognition and low-level perception).

[2] The present study uses coherent motion and synchronous motion as similar terms. However, as motion coherency or coherent motion reminds one of a specific type of visual stimulus (i.e., several elements moving straightforward in a coherent direction), "synchronous motion" will be used hereafter to address the stimuli implemented and manipulations within the present study.

[3] A linear multiple regression analysis was also performed for each dot-interaction condition, separately, with the rating score as a dependent variable and subject and smoothness as independent variables. The slopes were significant in all conditions (single, −0.97; independent, −0.83; semisynchronous, −0.56; synchronous, −1.00/smoothness; all $t > 8.39$, $p < 0.001$).

[4] The regression analyses showed that the slopes were not significant for all but the synchronous condition (single, 0.05; independent, 0.06; semisynchronous, −0.04/smoothness; all $t < 0.58$, $p > 0.56$; synchronous, −0.67/smoothness; $t = 7.57$, $p < 0.001$).

[5] A narrower range of motion smoothness was used since the low-pass filter could not modulate smoother motion while the high-pass filter nearly made the smoother motion static.

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Appendix A

The motion profile of a stimulus dot was generated based on the following procedure.

$$
\begin{aligned}
x &= -N/2, -N/2 + 1, ..., N/2 - 1\\
d &= \sqrt{2x^2} + 10^{-5}\\
Z &= \left| F^{-1}\left(S^{-1}\left(d^{-\alpha}\exp(2\pi i U)\right)\right)\right|\\
p_i &= Z_i/\max(Z)
\end{aligned}
\tag{A1}
$$

where N is 225 (75 frames per second $\times$ 3 s), U is a uniform random series, S^{-1} is the inverse fast Fourier transform (FFT)-shift operator that swaps the left and right halves of a series, F^{-1} is the inverse FFT, and α is the smoothness factor. The α controls decay of amplitudes along with frequency; a larger α leads to larger decay, which means amplitudes of high frequency bands are relatively smaller than those of low frequency bands. The Perlin noise series, Z, was generated separately for the horizontal and vertical position. The p_i is the vertical or horizontal position of the i-th frame. The p_i ranges from 0 to 1, where 0 corresponds to the lower limit (bottom or left edge), and 1 corresponds the upper limit (top or right edge) of the dot's region.