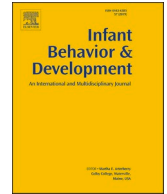




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Infant perception of causal motion produced by humans and inanimate objects

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ABSTRACT

Both the movements of people and inanimate objects are intimately bound up with physical causality. Furthermore, in contrast to object movements, causal relationships between limb movements controlled by humans and their body displacements uniquely reflect agency and goal-directed actions in support of social causality. To investigate the development of sensitivity to causal movements, we examined the looking behavior of infants between 9 and 18 months of age when viewing movements of humans and objects. We also investigated whether individual differences in gender and gross motor functions may impact the development of the visual preferences for causal movements. In Experiment 1, infants were presented with walking stimuli showing either normal body translation or a “moonwalk” that reversed the horizontal motion of body translations. In Experiment 2, infants were presented with unperformable actions beyond infants’ gross motor functions (i.e., long jump) either with or without ecologically valid body displacement. In Experiment 3, infants were presented with rolling movements of inanimate objects that either complied with or violated physical causality. We found that female infants showed longer looking times to normal walking stimuli than to moonwalk stimuli, but did not differ in their looking time to movements of inanimate objects and unperformable actions. In contrast, male infants did not show sensitivity to causal movement for either category. Additionally, female infants looked longer at social stimuli of human actions than male infants. Under the tested circumstances, our findings indicate that female infants have developed a sensitivity to causal consistency between limb movements and body translations of biological motion, only for actions with previous visual and motor exposures, and demonstrate a preference toward social information.

1. Introduction

Viewed through the eyes of an infant, the world is full of potentially perplexing movements: a toy car slides away from her and bumps into a caregiver; the caregiver extends an arm to grasp the toy car and swings her legs to walk towards the baby. This dynamic everyday situation is intimately bound up with causality. The wheels of the toy car rotate in one direction to cause the toy to move away; the caregiver moves her legs in a certain way that causes her body to move towards the infant. Physical causality can be manifested in the movements of a single inanimate object or an animate agent. One characteristic attribute of causal relations is the expected consistency between two motion signals: Relative movements within an object-centered reference frame act as causes (e.g.,

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rotation of a wheel, swinging of body limbs), and global translation of an object or a person within an environmental reference frame act as effects (e.g., translation of a rolling ball, body position displacements of a walker). Such causal relations between local relative movements and global translation are prominent in dynamic stimuli. Furthermore, human actions are special in that they control interactions with the world and afford privileged access to the experience of agency, in contrast to inanimate movements. Thus, for human infants, the understanding of the causal consistency in human movements may serve as the key foundation for understanding and predicting social actions.

Are young infants sensitive to the causal relation between local movements and the translation of human agents and inanimate objects? The answer is unclear. On the one hand, there is strong evidence that within the first year after birth, infants start to develop an understanding of dynamical movements for both inanimate objects and human agents. Infants distinguish causal launching events (Michotte, 1963) from similar but noncausal events in which a temporal delay is added during the contact of the two objects (Leslie & Keeble, 1987). Oakes and Cohen (1990) obtained similar findings for 10-month-old infants using real toys with wheels. Other evidence suggests that infants may possess a causal framework for reasoning and learning about physical interactions (e.g., Baillargeon et al., 2012; Kotovsky & Baillargeon, 1998; Luo, Baillargeon, Brueckner, & Munakata, 2003), as well as social interactions (Waismeyer & Meltzoff, 2017).

However, most previous studies have examined physical and social causality based on the interaction of two objects or two agents. Two-object interactions with contact entail characteristic spatiotemporal cues in the motion stimuli (e.g., contact of one object with another followed by motion of the second object), and infants' sensitivity to causal events could be driven by the detection of these features, rather than by appreciation of physical and social causality *per se* (Leslie, 1982). These spatiotemporal cues are absent in the case of causal movements of a single object. It remains unclear, therefore, whether infants can distinguish movements that comply with versus violate physical causality for displays of single entities.

When movements of an object violate the causal expectation, an impression of awkwardness or surprise can arise. One classic example of the violation of causal expectation for biological motion is the "moonwalk" dance move popularized by the dancer Michael Jackson. In the moonwalk, the limb movements of a dancer appear to simulate walking forward, while the whole body of the dancer glides seamlessly *backward*, creating a dramatic conflict in the expected relations between limb movements and body displacement. Adults show sensitivity to degrees of consistency between displacements of body position and limb movements (Masselink & Lappe, 2015; Peng, Thurman, & Lu, 2017) in a range of tasks involving action perception and inference.

Sensitivity to translational displacement of the human body may constitute a critical step in the development of biological motion perception and social perception. Three-day-old infants demonstrate a preference for a walker showing translational displacement of the body relative to an actor walking in place (e.g., on a treadmill; Bidet-Ildei, Kitromilides, Orliaguet, Pavlova, & Gentaz, 2013). This finding highlights the apparent role that body translational displacement may play in early visual competence in action perception. In addition, recent behavioral and neural studies yielded converging evidence that infants are sensitive to the directionality conveyed by limb movements of human walkers. For example, Bardi, Di Giorgio, Lunghi, Troje, and Simion (2015) found that walking direction of a point-light walker displayed in the central area can trigger covert peripheral attention in 6-month-old infants. The finding was further supported by EEG evidence showing that the P1 event-related potential component was larger in response to targets on the congruent side of walking direction of a point-light walker for both 3- and 6-month-old infants (Lunghi, Piccardi, Richards, & Simion, 2019; Lunghi, Di Giorgio, Benavides-Varela, & Simion, 2020). Together, the existing evidence has revealed that in early development infants are sensitive to the body translation and directionality conveyed by a point-light walker. However, it remains unclear whether infants are sensitive to the relation between body displacement and appropriate limb movements—what we term the *motion consistency constraint* in compliance with physical causality. It is also uncertain whether the ability to distinguish causal movements from motions defying causality develops in parallel for both human actions and inanimate objects, or shows different development trajectories for social versus physical stimuli.

In addition to investigating general development of sensitivity to motion consistency, we also examined whether individual differences in gender and gross motor functions may impact the development of the visual preferences for causal movements. Considerable evidence supports a sex difference in the allocation of attention towards animate/social versus inanimate/physical motions. For example, Connellan, Baron-Cohen, Wheelwright, Batki, and Ahluwalia (2000) found that male neonates showed a stronger interest in a physical-mechanical mobile, whereas female neonates showed a stronger interest in social stimuli such as faces. By four months, girls appear to be more interested than boys in "chasing" dot interactions (Frankenhuis, House, Barrett, & Johnson, 2013), suggesting a biological origin of the sex difference. In addition to gender differences in motion perception for human and object movements, previous research has also shown that motor development and cognitive development in childhood are fundamentally interrelated (e.g., Diamond, 2000). Some studies suggest that motor developments in infancy may be closely linked with perception of causal movements, especially as related to actions. Waismeyer and Meltzoff (2017) found that by 24 months, infants can learn to produce motor responses that lead to the desired outcome based solely on visual observations of social and physical causal events. It is possible that performing goal-directed actions may reciprocally reinforce the perception of phenomenal causality in dynamic events. Hence, studying the relation between causal perception and gross motor developments during a period of rapid gross motor development in infancy may shed light on the fundamental connections between motor development and cognitive development in early childhood.

The present paper reports three experiments that examine the influence of the motion consistency constraint on infants' perception of both biological motion and physical movements of objects. Instead of using two motion events in which one causally triggers the other (e.g., Leslie & Keeble, 1987; Oakes & Cohen, 1990), we developed a paradigm to test sensitivity to causal consistency between motion cues (limb movements versus body displacements) embedded in a single entity. This paradigm makes it possible to control potential confounding variables based on spatiotemporal factors and visual kinematic information. Both causal congruent motion and incongruent motion included the same kinematic cues for the same object or actor, and only the relation between motion signals was

manipulated. Experiment 1 used walking actions as stimuli. The causal condition showed normal walking actions, whereas the noncausal condition showed “moonwalk” actions that reversed the horizontal motion of body translations. Experiment 2 used unperformable actions of long jumps and sideways walking, which are beyond gross motor functions of infants between 9 and 18 months of age. The causal and “impossible” noncausal conditions were created in the similar way as in Experiment 1 by manipulating body displacements. Experiment 3 used rolling movements of objects as the stimuli to manipulate physical causality. The causal condition showed normal rolling motion, whereas the “impossible” noncausal condition showed movements that reversed the translation direction. We recorded infants’ eye movements as they viewed the two kinds of stimuli side-by-side. For all three studies, we reasoned that consistently greater attention to one of the two movements (normal vs. violation), as measured by longer looking durations, constitutes evidence that infants can differentiate visual stimuli based on differences in causal motions.

Previous studies have shown an inborn predisposition for processing intact biological motion. For example, infants exhibit a visual preference for a canonical point-light human walker over an inverted walker or random motion (Bardi, Regolin, & Simion, 2011; Fox & McDaniel, 1982; Simion, Regolin, & Bulf, 2008). Thus, we hypothesized that the pattern of infants’ eye movements might reflect a visual preference for normal walking over moonwalking, if they can successfully discriminate causal congruency from incongruent motions. In addition, given the previous finding that 4-month-old girls are more interested than boys in social stimuli (Frankenhuis et al., 2013; but see Tsang et al., 2018), we hypothesized that female infants might pay greater attention to human motions that entail social information, and also show a greater preference for human walking actions that exhibit causal motion consistency. To investigate the relationship between motor development and the visual perception of causal motion consistency, we collected behavioral measures with a gross motor questionnaire to assess the individual differences in gross motor functions. We hypothesized that achieving certain milestones of gross motor functions (e.g., walking) may be associated with a stronger sensitivity to causal consistency in human walking actions.

2. Experiment 1: causal consistency in biological movements of human walkers

Experiment 1 was designed to assess whether infants in the age range of 9–18 months have developed the sensitivity to causal movements of biological stimuli, such as human walkers. We selected this age range based on existing evidence concerning the rapid development of causal perception and gross motor functions during this time (e.g., Oakes & Cohen, 1990; Waismeyer & Meltzoff, 2017). We aimed to examine how the causal perception of human movements may develop in parallel with the development of motor functions in individual infants. Given that fine discrimination of human actions develops around age one year, we expected that the infants would show behavioral patterns differentiating normal actions from actions that violate motion consistency (i.e., moonwalk).

2.1. Methods

2.1.1. Participants

To determine the required sample size, a priori power analysis was conducted using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). We adopted the effect size reported in a previous study on the gender difference in biological motion perception in infancy (Tsang et al., 2018). To detect a within-subject group difference in visual preference toward biological motion with an estimated effect size of 0.53 ($M_{\text{difference}} = 0.08$, $SD_{\text{difference}} = 0.15$) between measures of looking time for the two display conditions (novel vs. familiar point-light displays), a sample size of 29 is needed to achieve a power of 0.8. In Experiment 1, a sample of 35 healthy infants (17 male and 18 female) between 9.4 and 18.04 months ($M = 13.48$ months, $SD = 2.86$ months) completed the study. Female and male infants were matched on age in months (female $M(SD) = 13.7(3.4)$, male $M(SD) = 13.3(2.3)$, $p = 0.713$) (for distribution, see supplemental Fig. S1). Five additional babies were observed but excluded from the final dataset due to excessive fussiness. Parents and caregivers were contacted by telephone from lists of birth records provided by Los Angeles County. Parents were given a small gift (a toy or a t-shirt) for their participation. Participants in both experiments were treated in accordance with University IRB #10-000619 “Brain Mechanisms of Visual Development.”

2.1.2. Stimuli and apparatus

Action stimuli were generated from the Carnegie Mellon University Motion Capture Database (<http://mocap.cs.cmu.edu>) and processed using the Biological Motion Toolbox (van Boxtel & Lu, 2013a). We selected two walking actions with whole-body movements, including “walk and turn” and “walk and turn-in-place.” Each action lasted 16 s, with the person walking from one side of the video to another, making a turn, and coming back. Skeletal displays were generated by connecting 13 main joints of the body: the head, shoulders, elbows, wrists, hips, knees, and ankles. Skeletal displays were chosen to eliminate appearance information in human action stimuli, such as facial expression, clothing, body shape, and gender. The skeletal display keeps the least amount of information signaling the body structure and motion of a human. We did not use point-light display as in previous infant motion perception studies (Ogren, Kaplan, Peng, Johnson, & Johnson, 2019; Tsang et al., 2018) because the current investigation aims to focus on the relationship between limb and body movements, instead of the perceptual grouping of joints.

The size of image frames was 21.3 by 17.1° of visual angles. The lower half of image frames included a checkerboard floor. The height of skeletal actors was normalized for all actions as 9.5° of visual angle. The vertical locations of the hip points were placed at the vertical center in the first frame of the video. The average horizontal locations of the hip points in each video were kept at the horizontal center. Body displacements were computed as the change in the average position of the two hip joints in time, and limb movements were defined as the residual motion after subtracting body displacements on a frame-by-frame basis (Peng et al., 2017). For both actions, a moonwalk action was generated by reversing the horizontal direction of body displacements (see illustration in Fig. 1,

top panel). Speeds of actors were controlled to be the same across normal action and moonwalk conditions, with an averaged horizontal translational speed of about 4/s. The stimuli used in the experiments can be viewed at https://osf.io/hk34g/?view_only=a23ed577ac1c4e5da8c239119ca2369b.

Experimental stimuli were generated with Experiment Builder software, the software associated with the eye tracker (SR Research EyeLink 1000) used to collect infants' looking time to the stimuli. For our primary analyses of interest, infants' point of gaze was coded with respect to two "areas of interest" (AOIs), each fully encompassing a video stimulus on each side of the center of the screen. The dependent variable for all analyses was calculated as the total dwell time (accumulated fixations) that was focused within a given AOI.

To measure the gross motor functions of infants, a questionnaire was developed by selecting a subset of 10 questions from the Early Motor Questionnaire (EMQ) (Libertus & Landa, 2013). The ten questions measure infants' gross motor abilities in sitting, standing, walking, running, and jumping (see the Supplementary Material). The measurements are based on reports from caregivers on a scale from -2 to 2 , with -2 indicating "Sure that child does NOT show behavior" and 2 indicating "Sure that child shows this behavior and remember a particular instance," yielding a maximum score of 20 for all ten questions and a minimum of -20 .

2.1.3. Procedure

We used an EyeLink 1000 eye tracker (SR Research, Ottawa, ON) to record infants' eye movements, with a sampling frequency of 500 Hz and a spatial accuracy of approximately 0.5° to 1° visual angle. Before the experiment, a caregiver provided informed consent and completed the gross motor questionnaire. Prior to testing, each infant's point of gaze was calibrated to coordinates on the screen with a standard 5-point calibration routine. During calibration, an attention-getting stimulus was presented at five locations on the screen (the four corners of the screen and the center) as the infants tracked their locations. The experimenter controlled the progression through the stimuli, moving on to the next calibration location only once the child had fixated on the prior location. If the calibration for a particular location was poor, it was repeated. After initial calibration, this process was repeated for validation. If the validated fixations were within 1° visual angle from the calibration fixations, the calibration was accepted. If not, the calibration procedure was repeated until this threshold was met. The experimental session began only after the calibration criterion had been reached.

During testing, each infant sat on a caregiver's lap approximately 55 cm from a 61.5 -cm monitor. Parents were instructed to hold their infant on their lap and allow their child to look freely during the session. They were also asked not to talk to their infant, point to the screen, or otherwise influence their infant's looking pattern. On each trial, one normal action with matched body translation and one moonwalk action with reversed translation were shown side-by-side for 16 s (see Fig. 1, bottom panel). The actors in the two videos shared the same facing direction and the starting pose. The experiment included eight trials, with display order of actions randomized.

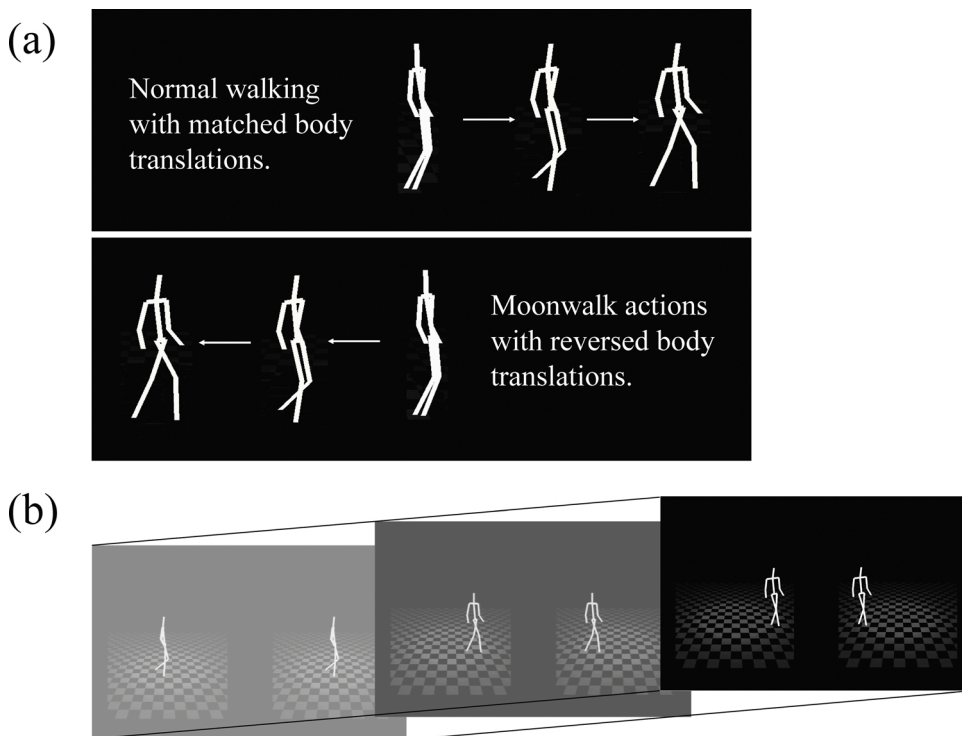


Fig. 1. Stimulus illustration in Experiment 1. (a) Illustration of a normal action with matched body translations and a moonwalk action with reversed body translations. Limb movements were the same in the two conditions, except that in the moonwalk condition, body translations were reversed in the horizontal direction. (b) Sample frames. Lighter to darker color represents frames from earlier to later in time. In each frame, a normal action with matched body translations and a moonwalk action with reversed body translations were presented side-by-side. Human actions were displayed in the skeletal form on a static checkerboard background representing the floor.

Each action pair (normal versus moonwalk) was repeated four times: two trials with leftward facing direction, and two trials with rightward facing direction. Half of the trials showed the normal action on the left side and the other half showed the moonwalk action on the left side. An attention-getter was shown at the beginning of each trial to orient the infant’s gaze to the center of the screen. The experimenter controlled the progression of between-trial breaks, moving on to the next trial only once the child had fixated on the attention-getter. The mean duration of the experiment was around 2 min to complete all eight trials. The total looking time for each action on each trial was recorded, along with the dwell time to each AOI.

2.2. Results and discussion

Six out of 35 infants yielded missing data in some trials, as they looked away from the screen. The number of missing trials was in the range of 1–2 trials per subject, and the missing trials occurred towards the end of the experiment. Although the experiment consisted of only eight trials, infants showed decreased looking time to the screen over trials ($F(7, 28) = 3.23, p = .012$) (see supplemental Fig. S3). Additionally, a Box’s Test of Equality of Covariance Matrices showed that infants’ looking time data showed unequal variability across trials ($p = .004$). Some variability resulted from the systematic effects, such as shorter looking time in later trials due to habituation and/or fatigue, and some variability was likely due to attention fluctuation across trials. Accordingly, we employed a linear mixed-effects model in Stata to analyze looking time data across trials. In addition to its ability to handle missing data, this model can take into account correlated data in repeated measurements and unequal variances across trials and subjects. The factors of walking actions, gender, the two-way interaction between types of walking and gender, and trial were entered as fixed effects. No random effect was modeled. Age was entered as a covariate. The model included an unstructured covariance matrix due to the unknown structure of covariance between trials and walking conditions. The model fitting reached both convergence and significance ($F(11, 27.52) = 6.98, p < .001$). The likelihood-ratio test showed that the mixed linear model yielded significantly better goodness of fit than a simple linear model ($\chi^2(135) = 254.87, p < .001$), supporting the use of a linear mixed model for analysis. Effect sizes of significant fixed effects reported below are standardized coefficients (Lorah, 2018; Nieminen, Lehtiniemi, Vähäkangas, Huusko, & Rautio, 2013).

Fig. 2 shows the average looking time per trial across normal walking and moonwalk for female and male babies (also see Fig. S4 in supplemental materials for distributions). The mixed-effects model revealed a significant two-way interaction between types of actions and gender ($t(29.4) = 3.54, p = .001, \beta = 0.41$). Female infants looked longer to normal walking actions ($M_{adjusted} = 5572.3 \text{ ms}, SE = 316.9$) than moonwalk actions ($M_{adjusted} = 4625.4 \text{ ms}, SE = 283.0$), yielding a significant simple main effect for female infants ($t(30.7) = 3.75, p = .001, \beta = 0.15$). The different looking time between normal walking and moonwalk suggests that female infants have developed the sensitivity to motion consistency between limb movements and body displacements in walking actions. However, male infants did not show a significant difference between looking times to normal versus moonwalk actions ($t(31.2) = 0.82, p = .417, \beta = 0.04$). This sex difference in sensitivity to motion consistency in walking actions suggests that female infants are more sensitive than male infants to subtle deviations from normal actions in biological motion stimuli. Additionally, female infants looked longer at normal walking actions than male infants, yielding a significant simple main effect for normal walking actions ($t(13.6) = 2.42, p = .030, \beta = 0.15$). This gender effect is consistent with previous findings indicating that female infants are more interested in displays with social information (Connellan et al., 2000). The gender difference was not significant for the looking time to moonwalk videos ($t(20.4) = 0.68, p = .506, \beta = 0.04$).

Here, female infants showed a familiarity preference to the normal walking actions instead of a novelty preference to moonwalk stimuli. This result is consistent with previous evidence showing that familiarity preference is often present earlier than novelty preference. With brief exposure to a stimulus in a novel display (such as skeletal figure of human body in our study), infants usually demonstrate a familiarity preference at first, which is only replaced by a novelty preference upon further exposure to the familiarized

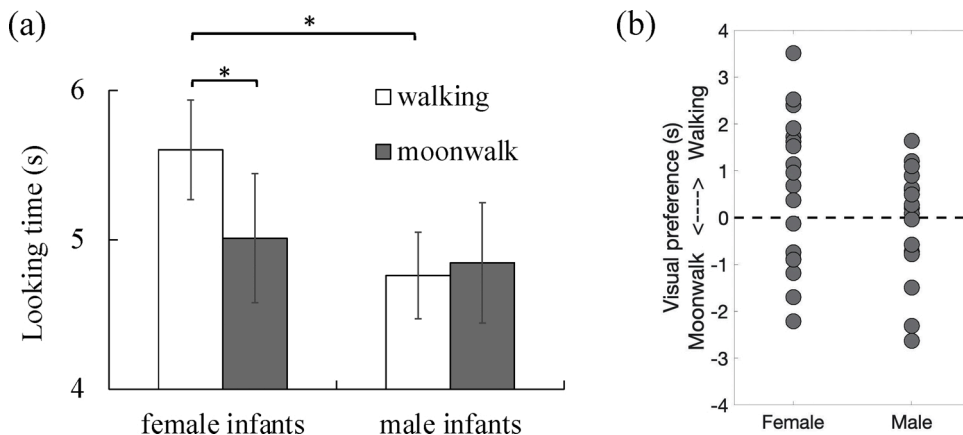


Fig. 2. Results of Experiment 1. (a) Mean looking time per trial across normal walking and moonwalk for female and male babies. Error bars indicate 95 % confidence intervals. (b) Distribution of looking time differences between normal walking and moonwalk for female and male babies.

stimulus (e.g., Hunter & Ames, 1988; Wagner & Sakovits, 1986). Thus, the visual experience to common actions during the first year for infants may serve as critical exposures to actions performed in a causally congruent manner and drive the familiarity preference toward normal walking actions in the early stages of stimulus exposure. It is possible that, with prolonged exposure to action stimuli and motor development in support of performing actions, a novelty preference may emerge in later stages.

To further examine the robustness of the results, we used a more constrained Toeplitz covariance matrix and restricted the age range to below 15-month (8 infants removed, $N = 27$, $M (SD) = 12.25 (1.93)$). The results of the linear mixed model replicated a significant two-way interaction between types of actions and gender ($t(24.4) = 2.20$, $p = .038$, $\beta = 0.41$), as well as the significant simple main effect for female infants ($t(24.7) = 2.54$, $p = .018$, $\beta = 0.16$) and also a marginally significant simple main effect of looking time at normal walking between two genders ($t(33.3) = 1.77$, $p = .087$, $\beta = 0.19$). When we further constrained the age range to below 14-month (15 infants removed, $N = 20$, $M (SD) = 11.4 (1.47)$), the same model yielded a marginally significant two-way interaction between types of actions and gender ($t(17.6) = 1.74$, $p = .099$, $\beta = 0.32$), as well as a significant simple main effect for female infants ($t(18.3) = 2.48$, $p = .023$, $\beta = 0.16$). These results suggest a reliable visual preference for normal walking relative to moonwalking in female infants, even with a smaller sample size and a younger age range.

Foot movements are known to be important in biological motion perception (Troje & Westhoff, 2006; van Boxtel & Lu, 2015). However, the displacement of the upper torso carries indicative information for estimating heading direction and global body translation. To analyze whether infants paid greater attention to the upper torso or the lower body portion (including legs and feet), we further defined two AOIs within both videos: the upper half of the screen, containing arm movements, and the lower half of the screen, containing leg movements of the actions. The two hip points were aligned with the vertical center of the video at the beginning of each trial. However, hip points might bounce slightly between the upper half and the lower half of the video as the action was performed. A mixed ANOVA was conducted with spatial location (upper vs. lower regions of the display) as within-subject variables, gender as a between-subject variable, and looking time on as the dependent variable. As shown in Fig. 3, The main effect of spatial location was significant ($F(1, 33) = 12.24$, $p = .001$, $\eta_p^2 = .924$), with longer looking time at the upper half of the body ($M = 6323.12$ ms, $SD = 528.84$) than the lower half ($M = 3672.23$ ms, $SD = 338.26$). The longer looking time at the upper body may reflect a focus on body translations, since the torso and the head are relatively rigid parts, serving as good indicators of body positions in the environment. The main effect of gender ($p = .408$) and the two-way interaction between gender and spatial locations ($p = .889$) were not statistically significant.

Next, we examined whether age or gross motor skills correlated with looking behavior for walking stimuli. A composite score of gross motor skills was calculated for each infant by summing the scores for the ten questions on the motor questionnaire (for individual question responses, see supplemental Fig. S2). Among the 35 infants, 29 infants got completed survey data of gross motor function from caregivers. The difference of gross motor functions between female and male infants did not reach significance ($t(27) = .41$, $p = .683$; for the score distribution, see supplemental Fig. S2). Not surprisingly, age significantly correlated with gross motor skills ($r(30) = .70$, $p < .001$), with gross motor skills increasing with age. However, neither age nor gross motor skills significantly correlated with average looking time to normal walking or moonwalk, or the difference between these conditions (i.e., $T_{\text{normal}} - T_{\text{moonwalk}}$), or the total looking time (i.e., $T_{\text{normal}} + T_{\text{moonwalk}}$) ($ps > .23$). We further refined the motor assessment by focusing on the walking-related questions in the questionnaire. These assessments did not yield any significant correlations of gross motor development in walking functions with looking behaviors.

3. Experiment 2: causal consistency in actions that infants cannot perform

In Experiment 1 we found that female infants showed shorter looking time to moonwalk actions that violated causal congruency in motion relative to normal walkers. However, it is unclear whether such effect is driven by low-level motion cues such as the sliding motion of feet on the ground. In Experiment 2, we employed two additional actions, “long jumps with walk backward” and “walk sideways and turn”. These two actions were selected due to two reasons. First, both actions are not performable for 18-month infants due to gross motor immaturity, and also are not commonly encountered in infants’ daily life. Thus, we expected infants to have

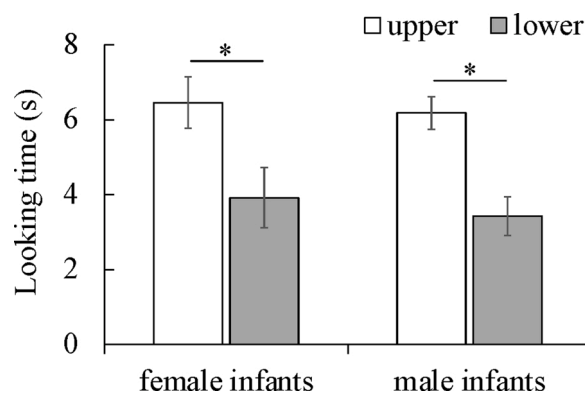


Fig. 3. Looking time to the upper and lower half of the body in Experiment 1. Error bars indicate between-subjects standard errors.

minimal visual and motor exposure to these actions. Secondly, to create the noncausal condition, horizontal motions of body translations in these actions were reversed as to how we generated the moonwalk in Experiment 1. Hence, in both Experiment 1 with walking actions and Experiment 2 with unperformable actions, the noncausal actions showed a common low-level feature such as “sliding-on-the-ground.” If the effect in Exp 1 was driven by low-level features of feet sliding on the ground, we expect to find similar results in Exp 2. In contrast, if the effect was mainly driven by causal expectations that certain limb movements lead to body translation in an action, we hypothesized that infants would not show an effect of visual preference between conditions in Experiment 2 due to the lack of visual/motor experience, and consequently causal representation of these tested actions.

3.1. Methods

3.1.1. Participants

A sample of 29 healthy infants were enrolled (17 male, 12 female), with ages between 9.07 and 18.40 months ($M = 12.86$ months, $SD = 3.01$). Four additional babies were observed but excluded from the final dataset due to excessive fussiness. Female infants yielded significantly older ages than male infants in the current sample ($M_{female}(SD) = 14.63(3.11)$, $M_{male}(SD) = 11.61(2.28)$, $t(27) = 3.02$, $p = .006$) (for distribution, see supplemental Fig. S1), but the difference between gross motor functions between female and male infants did not reach significance ($t(26) = 1.61$, $p = 0.120$; for the distribution, see Fig. S6).

3.1.2. Stimuli and procedure

As in Experiment 1, we selected two actions with whole-body movements from the Carnegie Mellon University Motion Capture Database, including “long jumps and walk backward” and “walk sideways and turn” (Fig. 4). Also as in Experiment 1, each action lasted 16 s, and skeletal displays were generated by connecting 13 main joints of the body. For each action, an impossible action was generated by reversing the horizontal direction of body displacements to create the noncausal condition. Speeds of actors were controlled to be the same across normal action and moonwalk conditions. The experiment included eight trials, with the two actions (i. e., possible and impossible actions) being presented in a randomly interleaved manner. Each action pair repeated four times, including two trials with leftward facing direction and two trials with rightward facing direction. The gross motor questionnaire was completed by a caregiver before the experiment.

3.2. Results and discussion

Seven out of 29 infants yielded missing data in some trials as they looked away from the screen. The number of missing trials was in the range of 1–2 trials per subject, and the missing trials occurred towards the end of the experiment. Even though infants still showed a trend of decreasing looking time to the screen over trial, the main effect of trials did not reach significance ($F(7, 20) = 1.58$, $p = .198$)

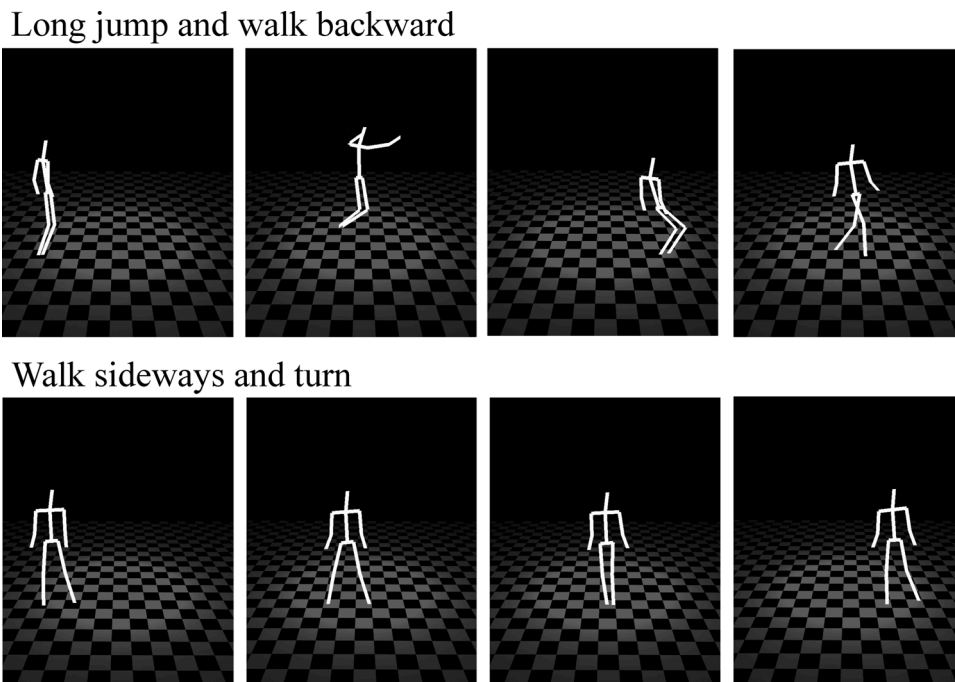


Fig. 4. Stimulus illustration in Experiment 2. Illustration of sample frames in the normal action sequence of a “long jump and walk backward” and a “walk sideways and turn”.

(see supplemental Fig. S7). We employed a linear mixed-effects model in Stata as in Experiment 1 to analyze looking time data across trials. We used the same model settings as in Experiment 1. The model fitting reached both convergence and significance ($F(11, 5.61) = 26.02, p < .001$). The likelihood-ratio test showed that the mixed linear model yielded significantly better goodness of fit than a simple linear model ($\chi^2(135) = 273.93, p < .001$), supporting the use of a linear mixed model for analysis. As shown in Fig. 5, the mixed-effects model revealed a significant main effect of gender ($t(29.4) = 3.76, p = .002, \beta = 0.16$) as female infants looked longer to action stimuli than did male infants. In addition, the model also revealed a significant main effect of age ($t(29.4) = 9.49, p = .002, \beta = 0.21$). A Pearson correlation between the total looking time and age revealed a significant positive correlation ($r(27) = .458, p = .012$), indicating that infants looked longer at the stimuli as they grew older. The main effect of motion consistency (normal vs. impossible actions, $p = .759$) and the two-way interaction between gender and motion consistency ($p = .429$) were not significant (for distributions of looking time, see supplemental Fig. S8). We also examined the robustness of the results using a repeated-measure ANOVA. Looking time data were collapsed across trials and we got similar results as in the linear mixed model (see supplemental material Section 3.3).

To examine whether infants paid more attention to upper body regions as in Experiment 1, we extracted looking time to the upper half and the lower half of the screen, and conducted the mixed ANOVA with action category (long jump vs. walking sideways) and spatial location as within-subject variables and gender as a between-subject variable. We found a significant two-way interaction between action category and spatial location, $F(1, 27) = 4.95, p = .035, \eta_p^2 = .573$ (Fig. 6). Tests for simple main effects showed that infants demonstrated an upper-body preference for the action of long jumps and walk backward ($p = .004$), but the effect did not reach the significance for the action of walking sideways and turning ($p = .089$). We also found significant main effects of action category, $F(1, 27) = 18.03, p < .001, \eta_p^2 = .983$, with longer looking time to jumping action ($M = 6210.06$ ms, $SD = 239.42$) than walking sideways ($M = 5168.16$ ms, $SD = 184.87$), likely due to ballistic movements in jumping actions. The main effect of spatial location was also significant, $F(1, 27) = 7.19, p = .012, \eta_p^2 = .734$, showing longer looking time to the upper body ($M_{estimated} = 6737.54$ ms, $SD = 429.24$) than the lower half ($M = 4640.67$ ms, $SD = 427.61$), which is consistent with findings in Experiment 1 with walking actions. Gender did not show any significant interaction effects with action category ($p = .755$) or spatial location ($p = .770$). However, there was a significant main effect of gender, $F(1, 27) = 17.17, p < .001, \eta_p^2 = .979$, with female infants ($M = 6415.06$ ms, $SD = 268.29$) showing overall longer looking time to biological motion than male infants ($M = 4963.15$, $SD = 225.21$), consistent with Experiment 1.

4. Experiment 3: causal consistency in movements of inanimate objects

From Experiments 1 and 2, female infants demonstrated sensitivity to walking actions, but lack of discrimination of motion consistency in unperformable actions. In Experiment 3, we created analogous conditions to examine physical causality in the perception of object motion: an inanimate object rolling along a flat surface. The movements imitate what infants likely interact with in daily life when playing with a toy ball rolling on the ground. According to an “age-of-acquisition” dataset (Kuperman, Stadhagen-Gonzalez, & Brysbaert, 2012), “ball” is one of the first dozen noun words that children tend to acquire. Hence, the ball rolling motion is probably one of the most familiar physical movements of a representative object to infants. Experiment 3 aims to investigate whether the sensitivity to motion congruency in Experiment 1 is specialized for biological motion or it may generalize to movements of inanimate objects. The rolling movement of a round object is a combination of rotation and translation of the object. Most land vehicles use rolling wheels to move, with the translation of the object being caused by its rotation in rolling movements. We created two conditions: a rolling condition that exhibited causal consistency between local angular rotation and global translation and an “impossible” noncausal condition in which motion consistency is violated (Fig. 7A).

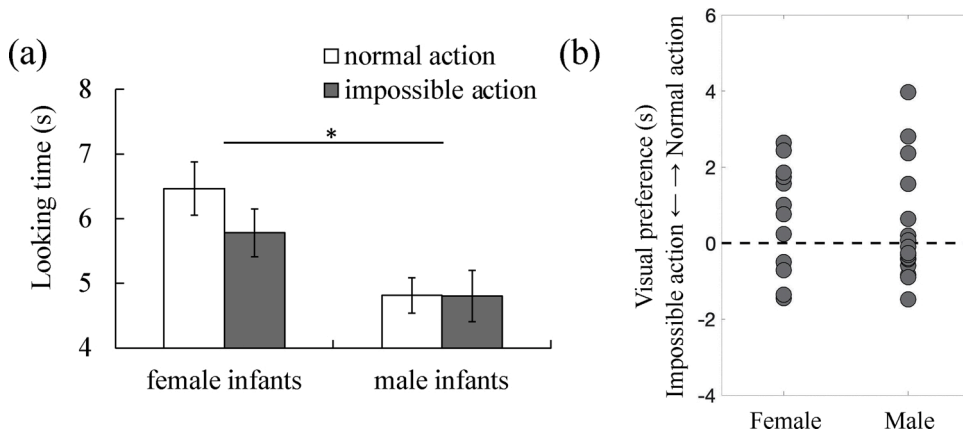


Fig. 5. Results in Experiment 2: (a) Mean looking time for female and male infants for normal and impossible actions. Error bars indicate between-subjects standard errors. (b) Individual visual preference revealed by looking time differences between normal and impossible actions for female and male infants.

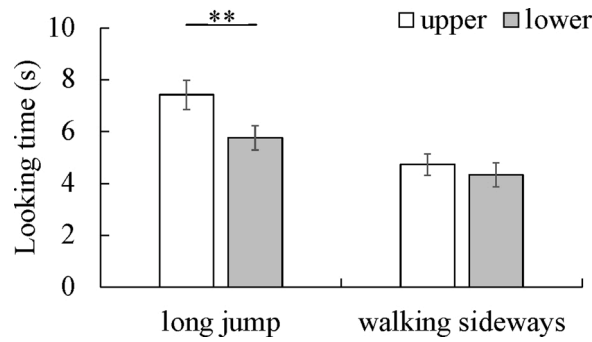


Fig. 6. Looking time to the upper and lower half of the body in Experiment 3. Error bars indicate between-subjects standard errors.

4.1. Methods

4.1.1. Participants

In Experiment 3, a sample of 31 healthy infants (17 male, 14 female) between 9.89 and 18.3 months ($M = 11.79$ months, $SD = 1.74$ months) completed the study. Female and male infants were matched on age (female $M (SD) = 11.8 (2.04)$, male $M (SD) = 11.8 (1.51)$, $p = 0.987$. For distribution, see supplemental Fig. S9). Four additional babies were excluded from the final dataset due to excessive fussiness.

4.1.2. Stimuli and apparatus

The stimuli were based on rolling movements of five objects, including three balls (a soccer ball, a basketball, and a beach ball), one gear, and one wheel. In the rolling condition (causal), translational velocity v of an object is determined by applying the physical equation to the objects' angular speed ω : $v = \omega \times r$, where r is the radius of the object. This physical constraint ensures that the ball will rotate clockwise to move rightward, and vice versa. In the impossible condition (noncausal), the angular rotation of the object remained the same as normal rolling objects, but the translational velocity of the object was reversed to the opposite direction (e.g.,

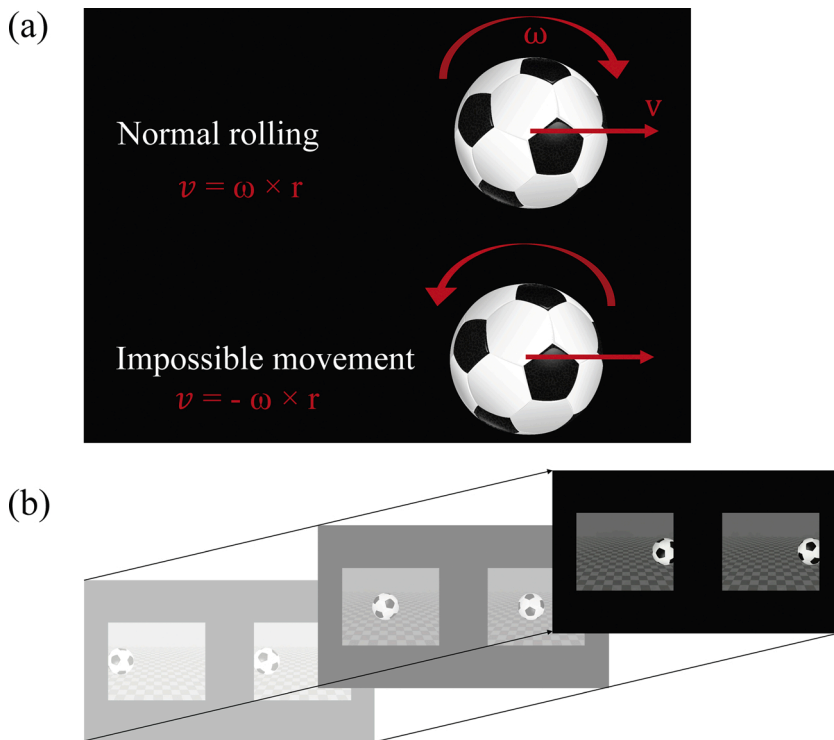


Fig. 7. Stimulus illustration in Experiment 3. (a) Illustration of a rolling movement with matched angular rotation and translational motion on top and an illustration of an impossible rotation that violates the relation between two motion signals. (b) Sample frames in Experiment 2. Lighter to darker color represents frames from earlier to later in time.

clockwise rotation combined with moving leftward). In the impossible rolling condition, the object appeared to skid on the floor. The size of image frames was 17.1° by 21.1° of visual angles. Individual objects were controlled to subtend about 5.7° of visual angle at the infant’s 55-cm viewing distance. The amplitude of angular rotation speed was $\frac{2}{3}\pi$ rad/second, resulting in a horizontal translational speed of about 5.97/s in normal rolling movements.

Each video clip lasted 10 s, with a ball appearing from one side of the video, moving towards the other side and disappearing, then reappearing and moving back with a reversed translation direction. The total looking time for each action on each trial was recorded by an EyeLink 1000 eye tracker.

4.1.3. Procedure

The general procedure was the same in Experiment 1 and 2. On each trial, two videos were shown side-by-side for 10 s (see Fig. 7B). One video showed normal rolling movements of an object with matched rotation and translation in accord with physical causality; the other video showed impossible movements of the same object with reversed rotation direction, which violates physical causality. Display sides of the normal rolling movements and impossible movements were randomly assigned across trials. We reduced the number of trials to shorten Experiment 3, due to the observation in Experiment 1 of a significant decrease in looking time for the last three trials (out of the total of eight). A total of five trials were presented in random order, with each trial showing one of the five different objects. On each trial, an object started from one side of the video to move towards the other side, disappeared for one second after hitting the frame boundary, and then reappeared and moved back with a reversed translation direction. The mean duration of the experiment was around 1 min to complete all five trials.

4.2. Results and discussion

Two out of 31 infants had missing data for one trial because they looked away during the entire trial so that no looking data were captured. The remaining trials of the two infants were included in the analysis. Similar to Experiment 1, infants showed decreased looking time over trials (Huynh-Feldt correction, $F(3.4, 101.4) = 4.55, p = .003$; see supplemental Fig. S10). A Box’s Test of Equality of Covariance Matrices revealed that infants’ looking time data showed marginally unequal variability across trials within individual subjects ($p = 0.082$). As in Experiment 1, we employed the same linear mixed-effects model to analyze looking time data across trials for object rolling movements. The model reached convergence and significance after seven iterations ($F(8, 19.92) = 3.65, p = .009$). The likelihood-ratio test showed that the mixed linear model yielded significantly better goodness of fit than a linear model ($\chi^2(54) = 183.57, p < .001$).

Fig. 8 shows the average looking time per trial across movement conditions for female and male babies (see supplemental Fig. S11 for distributions). The two-way interaction between type of ball movements and gender was not significant ($t(10.7) = 1.62, p = .134, \beta = 0.31$). None of the joint contrasts of main effects of gender and type of ball movements or simple main effects reached significance ($ps > 0.1$). We computed a post hoc power analysis to examine the interaction effect using G*Power 3.1 (Faul et al., 2007). With effect size of .31, alpha = .05, sample size = 31, and a correlation among repeated measures = .19, the data achieved power of .74. Therefore, Experiment 3 may have been underpowered to reveal possible interaction effects between gender and type of movements on visual preference for motion consistency.

5. General discussion

In three experiments, we investigated whether infants between 9 and 18 months are sensitive to motion consistency in biological motion of walking actions (Experiment 1), actions beyond 18-month infants’ gross motor functions (Experiment 2), and rolling

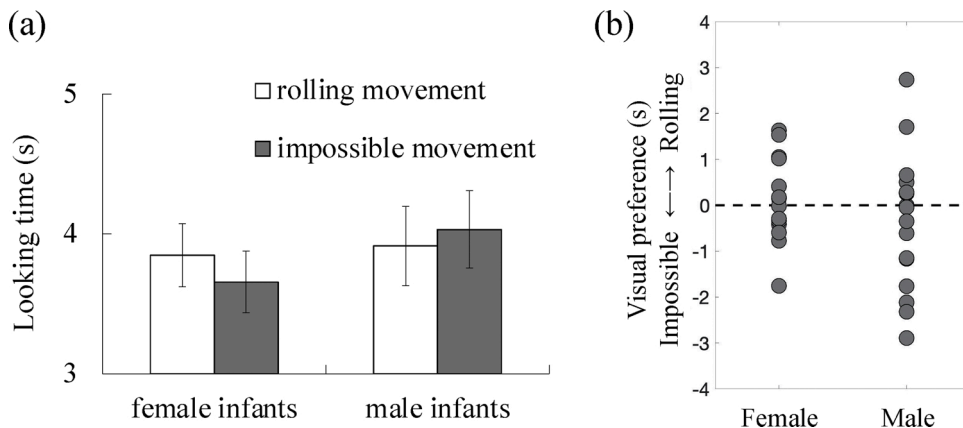


Fig. 8. Results in Experiment 3: (a) Mean looking time per trial for female and male infants for normal rolling movements and impossible movements. Error bars indicate between-subjects standard errors. (b) Individual visual preference revealed by looking time differences between impossible movements and rolling movements for female and male babies.

movements of physical objects (Experiment 3). Motion consistency is defined by causal expectation between relative movements of an object or a person (such as rolling, or limb movements) and global displacement of the object or the person in the environment. Three key findings emerged. First, we found that female infants can discriminate actions based on motion consistency between limb movements and body translations in walking actions. Specifically, female babies showed a familiarity preference for normal walking stimuli vs. a moonwalk, whereas male babies did not show a significant preference. Second, female infants showed longer looking times than male infants when looking at normal walking actions (Experiment 1), whereas no gender difference was observed in viewing rolling movements of inanimate objects (Experiment 3). Third, when observing actions that were beyond their gross motor functions and with which infants presumably have little visual experience, infants did not show a significant preference to normal actions (Experiment 2).

Even though both moonwalk and impossible rolling movement violate the causal relation that local movements of limbs or objects propel the global translation of the entity, infants' looking behaviors were different between the two experiments. These differences in infants' looking behaviors between the two experiments may seem to contradict some previous evidence concerning physical causality (Leslie & Keeble, 1987; Leslie, 1982; Oakes & Cohen, 1990; Woodward & Sommerville, 2000). For example, Oakes and Cohen (1990) found that starting at roughly 10 months, infants are sensitive to physical causality in that they distinguish launching events based on causal relations between items. Other evidence indicates that the development of causal perception may originate as early as six months (Leslie & Keeble, 1987). However, most previous results cannot completely rule out the possibility that infants rely on the spatiotemporal features jointly revealed by the two different entities, rather than causal relations between motion cues. These findings are consistent with the "object-first hypothesis" (Xu, 1999; Xu & Carey, 1996) which suggests that one-year-old infants represent objects as physically bounded, spatially separated entities persistent over time regardless of their differences in properties. Thus, by the end of the first year, young infants can use spatiotemporal information to track objects and interpret causal interaction between objects, but they disregard other detailed property information associated with objects. Hence, although previous findings suggest that by the end of the first year, infants can use spatiotemporal cues to judge how multiple objects interact in the physical world, it is unclear whether these results can be further generalized to more subtle relations between local and global motion cues within a single entity.

Even though the biological motion of walking actions may seem to be more complicated than simple ball rolling movements, infants demonstrated sensitivity to the violation of motion consistency for human actions but not for physical objects. This contrast was unlikely to be driven by differences in motor experience (e.g., walking and interacting with balls). By the time they participated in the experiment, a large proportion of infants being tested were not fully able to walk, let alone walk backward. However, most infants were perfectly able to crawl and sit, so presumably, they had a good chance of having played with balls and having watched the rolling movements. Thus, the stronger sensitivity to causal consistency in biological motion may be driven by visual observations of other agents such as walking of caregivers or benefit from some perceptual constraints specific to biological motion (Simion et al., 2008). The early emergence of sensitivity to the causal motion consistency in human actions may reflect its biological importance, as through the perception of translational motion people can assign a spatial goal to the perceived motion (Craighero, Lunghi, Leo, Ghirardi, & Simion, 2016). Evidence indicates that at 10 months of age, the speed at which infants reach for a ball depends on whether their goal is to fit the ball into a tube or to toss it into a tub (Claxton, Keen, & McCarty, 2003). Even during the first hours of postnatal life, newborns are able to discriminate some visual cues indicating the presence of goal-directed actions (Craighero, Leo, Umiltà, & Simion, 2011). Thus, the sensitivity to causal motion consistency between limb movements and global body translation may be a fundamental step prior to making inferences and predictions about goal-directed actions.

The gender differences between the three experiments may suggest that female and male infants attribute attention differently towards animate/social and inanimate/physical motions. In both Experiments 1 and 2, female infants showed significantly longer looking time to biological motion than male infants. The current results are consistent with previous evidence that female infants may show an increased interest in social stimuli than male infants from an early age (e.g., Alexander & Wilcox, 2012; Lutchmaya & Baron-Cohen, 2002; but see Escudero, Robbins, & Johnson, 2013; Tsang et al., 2018), which is important because parents socialize girls differently than boys even starting in infancy (Clearfield & Nelson, 2006; Constantinescu, Moore, Johnson, & Hines, 2018; Sung, Fausto-Sterling, Garcia Coll, & Seifer, 2013) and there are gender differences in hormone levels early in life (prenatally and perinatally) that may affect social and cognitive function (Chapman et al., 2007; Hines, 2010). Neuroimaging evidence also shows that point-light actions activate cortical regions involved in social perception more strongly in females from childhood (Anderson et al., 2013). Additionally, 10-month-old girls exhibited a greater fixation preference for "chasing" interactions between two dots, as well as increased pupil dilation when attending to chasing, relative to boys (Frankenhuis et al., 2013). Taken together, these studies suggest that females may be more attuned to social stimuli than males as soon as the first year after birth. However, male infants may be more sensitive to low-level motion information in dynamic stimuli. Research on biological motion perception also suggests that male infants differentiate walking stimuli better than female infants relying on motion information such as dot speeds and motion spans (Tsang et al., 2018). For male infants in the current study, we did not find evidence for sensitivity to causal consistency in physical ball movements, which could potentially be due to relatively small sample size, an age range on the younger side, or stimuli-related parameters such as the speed of ball movements and the contrast or color. Future studies could examine the developmental trajectory of causal motion consistency of physical movements in comparison to biological motions.

Furthermore, the gender difference in the sensitivity to causally congruent motion between female and male infants may be related to a difference in the developmental trajectory of holistic vs. local information processing. Previous research with children and human adults suggested a global processing bias in boys and male adults, compared to females. For example, Kramer, Ellenberg, Leonard, and Share (1996) enrolled boys and girls between the ages of 4 and 12 years to perform a perceptual judgment task and found that boys demonstrated significantly stronger global biases in their perceptual judgments than girls at all ages. Additionally, younger children of

both sexes were less global than older children. Later studies by Roalf, Lowery, and Turetsky (2006) used event-related brain potential (ERP) to compare hemispheric asymmetries and processing biases in adult men and women. The authors found that women responded more quickly to local targets while men did not differentially respond to hierarchical stimuli, which may suggest that women allocated greater attentional resources towards local, as opposed to global stimuli. However, both previous studies used stimuli of letters and shapes that do not involve any social or motion information. It is possible that dynamic social stimuli such as human actions have special status in perception. For instance, global processing is one of the fundamental component underlying biological motion and social understanding, which contributes to the differentiation among individual with high and low degrees of autistic traits (van Boxtel & Lu, 2013b; van Boxtel, Peng, Su, & Lu, 2017). Given the early interest in social stimuli among female infants (e.g., Alexander & Wilcox, 2012; Lutchmaya & Baron-Cohen, 2002), it is possible that female infants may show a stronger global processing bias than male infants for social stimuli such as human actions in early development. However, empirical studies are needed to examine the hypothesis.

Another intriguing finding is that infants showed a preference for the upper half of the moving body than to the lower half body in both Exp 1 and 2. This result seems inconsistent with previous findings with adults showing high sensitivity to movements of feet for the perception of walking actions (Troje & Westhoff, 2006), and also inconsistent with a previous report that infants display far greater interest in lower and middle regions versus the top region in point-light displays depicting human biological motion (Tsang et al., 2018). However, both studies used displays showing walkers moving in place without body translation. When a person moves around, the upper torso part of a moving body is close to rigid and hence can provide more reliable estimate of spatial location of the body in the environment. The attention to the upper body observed in the present study implies that infants have a basic understanding regarding where to look for reliable extraction of the location of a moving person. This preference exhibited in the 9–18-month olds may also result from greater motor experience in moving their upper body. With most infants developing the ability to crawl around 7–10 months and walk around 9–12 months, interactions are dominated by upper-body movements such as reaching for parents and grasping objects in the early infancy. The rich experience with upper-body movements may also contribute to selective attention to the upper half of displays of bodies in motion.

The ability to detect the violation of the motion consistency constraint in Experiment 1 was not related to the development of gross motor functions between the age range of 9–18 months. This may suggest that the sensitivity to motion consistency in biological motion becomes established in early development regardless of whether infants can perform the corresponding actions or not. However, this does not suggest that the development of motor functions and cognitive functions supporting action understanding are independent processes. As shown in Experiment 2, basic visual and motor experience may be fundamental to the development of sensitivity to motion consistency. Numerous evidence has shown that the development of motor experience may enable rapid developments in multiple cognitive domains, including 3D object recognition (Soska, Adolph, & Johnson, 2010), holistic face processing (Cashon, Ha, Allen, & Barna, 2013), and language development (He, Walle, & Campos, 2015; Walle & Campos, 2014). Additionally, the development of cognitive functions may reciprocate the development of gross motor functions. Such connections may serve as a building block for the development of mirror neurons (Rizzolatti, Fogassi, & Gallese, 2001) to link observed actions with internally generated actions (e.g., Rizzolatti & Arbib, 1998; Rizzolatti & Fadiga, 1998).

The current study has two major limitations. Although the study demonstrates that female infants show a visual preference for biological motion that accords with the motion consistency constraint, the results cannot rule out the possibility that infants rely on familiarity or specific spatiotemporal features that signal consistency in human body movements without necessarily relying on a causal understanding between limb movements and body translation. For example, infants may prefer biological motion stimuli in which the facing direction of a walker is consistent with the walking direction of body displacement, a common relationship in daily life. The expected binding between the facing direction and the walking direction usually signals normal walking movements. Hence, detection of the presence versus absence of this binding may lead to a visual preference for biological motion that complies with causal movements. Another possibility is that moonwalk actions introduced some low-level visual cues such as “sliding-on-the-ground” motion cues which could serve as an indicator for unnatural or less-biological motions. However, if the detection of sliding-on-the-ground movement was the key to infants’ visual preference, we would expect that unperformable human actions in Experiment 2 and rolling movements in Experiment 3 would also have shown group differences, as similar sliding motion signals were also present in impossible movements. The apparent lack of sensitivity to motion congruency in Experiments 2 and 3 argues against the possibility that infants used the cue of sliding-on-the-ground as a basis for discriminating between normal actions and violations, but some other more complex spatiotemporal features may still contribute to the effect.

The second limitation of the current study is related to the comparison between human movements and object motion in the two experiments. The current study cannot rule out the possibility that the differences between human and object movements were driven by low-level visual features of human figures and physical objects. For example, violation of causal relations may be more readily perceived in vertical stick-like human figures than in objects with round shapes. Moreover, the infant sample in Experiment 3 with rolling movements of objects showed a distribution of age skewed to younger months, with an overall younger average age than Experiment 1 and 2 (mean age 13.48 months in Experiment 1, 12.96 months in Experiment 2, and 11.79 months in Experiment 3). The two-month difference could undermine the chance of revealing a visual preference on motion consistency of physical movements in Experiment 3. In future studies, causal perception of human actions in infants can be examined with more targeted paradigms to gain a deeper understanding of the developmental trajectory connecting causal perception with action perception. For example, inverted displays of biological motion could be used to control for low-level visual features, and physical objects that demonstrate stronger directionality information such as ellipse-shaped or star-shaped objects could be created that have contours more similar to human figures.

Note

The data that support the findings of this study are openly available at https://osf.io/hk34g/?view_only=a23ed577ac1c4e5da8c239119ca2369b.

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Author contributions

Y. Peng, H. Lu, and S.P. Johnson developed the study concept and study design. Y. Peng programmed the study and conducted data collection. Y. Peng performed data analysis and interpretation under the supervision of H. Lu and S. P. Johnson. Y. Peng drafted the paper, and H. Lu and S. P. Johnson provided critical revisions. All authors approved the final version of the paper for submission.

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Appendix

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