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Infants' saccadic behavior during 2-dimensional displays of a bounce

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A R T I C L E I N F O

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A B S T R A C T

The study examined the saccadic behavior of 4- to 10-month-old infants when tracking a two-dimensional linear motion of a circle that occasionally bounced off a barrier constituted by the screen edges. It was investigated whether infants could anticipate the angle of the circle's direction after the bounce and the circle's displacement from the location of bounce. Seven bounce types were presented which differed in the angle of incidence. Three of the seven bounce types showed physically implausible bounces. Saccades that started before the infant could perceive the bounce and ended after the bounce were analyzed. Infants' saccades matched the circle's displacement with sufficient accuracy to conclude that they made predictive saccades. Only results from two bounce types where the circle's speed was less than 12.5°/s allowed for the possibility that infants made reactive saccades. The infants' anticipated angle was close to the angle of the circle's direction after the bounce. When the circle was moving at 40°/s, the difference between the two aforementioned angles was less than 15°, but it increased as the circle became slower. The effect of age on the saccade targets and other object-tracking measures was small and mostly masked by a large estimation error. Estimates of the saccade amplitude, saccade frequency, and the gaze-circle displacement were similar to those observed for saccades made when no bounce occurred and they were also similar to those reported in previous studies of infant object tracking with similar trajectories but without a barrier.

1. Introduction

In adults, the visual tracking of a moving object is achieved by a combination of saccades and smooth pursuit. *Smooth pursuit* helps to stabilize the moving object on the observer's retina for further inspection (Barnes, 2011). Smooth pursuit works well when the object is moving at a constant speed or when the speed and the direction of the object's motion change smoothly (Barnes, 2008). When this is not the case, smooth pursuit fails to maintain focus, and catch-up saccades help to bring the object back into focus (De Brouwer et al., 2002). Even though smooth pursuit was already observed in the first week of life (Lengyel et al., 1998), until 4 months of age smooth-pursuit episodes are short, infrequent, and fail to adapt to higher stimulus speed (Jacobs et al., 1997; Pieh et al., 2012; Shea & Aslin, 1990). The dominant object-tracking strategy in these young infants is to maintain tracking with the help of a rapid sequence of short saccades (Aslin, 1981). Between the first and fourth month of age, infants manage to maintain smooth pursuit for increasingly longer intervals (Phillips et al., 1997). As a consequence, saccades become less necessary, their frequency decreases, and the overall accuracy of object tracking increases (Rosander, 2007). Balkenius and Johansson (2007) argued that this transition is primarily driven

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by infants' increasing ability to anticipate target motions, rather than by improved oculomotor control. According to Balkenius and Johansson (2007), anticipation improves infants' ability to adapt their smooth pursuit to changes in stimulus speed. Anticipation also improves saccade targeting, resulting in a developmental shift from reactive to anticipatory saccades. Rather than minimizing the gaze-stimulus distance, the purpose of anticipatory saccades is to bring the gaze into a position from which the subsequent smooth pursuit can be efficiently resumed and maintained. Thus, rather than postulating a shift from saccadic tracking to smooth-pursuit-driven tracking (Rosander, 2007), according to Balkenius and Johansson (2007), infants shift from tracking with reactive saccades to tracking with a combination of smooth pursuit and anticipatory saccades. Rosander (2007) acknowledged infants' predictive abilities but attributed them to cerebellar and cortical maturation between 2 and 4 months of age. According to Balkenius and Johansson (2007), the anticipatory component of their model is already available at 2 months of age. Subsequent exposure to different types of motion allows infants to obtain an accurate representation of motion, which facilitates motion anticipation. This anticipation, in turn, leads to the documented improvement in object tracking in the first 4 months. Numerous published studies of infant object tracking are broadly consistent with the model by Balkenius and Johansson (2007), but also with the account of development of object tracking by Rosander (2007). Next, we discuss the supporting evidence and we identify four aspects of this literature that make it difficult to evaluate the two aforementioned accounts. The current study is outlined as part of this literature review. Its goal is to fill the four gaps highlighted by the literature review and thereby to advance the knowledge about infants' object tracking mechanisms and, in particular, the knowledge about the role of motion anticipation in this development.

First, a large number of demonstrations of anticipatory object tracking involve anticipation of simple motion properties, such as changes in object direction or changes in object speed. In particular, studies demonstrating accurate tracking in 4-month-old infants or younger have shown simple horizontal or vertical motions with a sinusoidal velocity profile and with a speed not exceeding 30°/s (Aslin, 1981; Jacobs et al., 1997; Pieh et al., 2012; Von Hofsten & Rosander, 1996). However, 4-month-old infants show difficulties when attempting to track objects at higher speeds (Jacobs et al., 1997; Von Hofsten & Rosander, 1997) or objects with more complex motion types such as triangular motion (Von Hofsten & Rosander, 1997), step-ramp motion (Shea & Aslin, 1990), circular motion (Gredebäck et al., 2005; Grönqvist et al., 2006), or motion changes determined by probabilities (Gredebäck et al., 2006). It takes further development in the first year of life for infants to show an accurate tracking of these complex motion types. Such an extended piecemeal stimulus-specific development of anticipatory object tracking is consistent with the claim by Balkenius and Johansson (2007) that it takes longer for infants to gain exposure to the less common motion types in order to master their tracking. However, in the case of some motion properties and motion types, it is also possible to explain the delayed development of their tracking by pointing to neurobehavioral studies that show delayed maturation of oculomotor and neural mechanisms associated with visual processing and tracking of these simple motion properties (Rosander, 2007). Such arguments become increasingly less compelling as evidence of early anticipation of very specific motion types increases. For instance, several studies indicated that adults use their knowledge of physics, such as the knowledge of transfer of momentum in collisions, to enhance their object tracking (Badler et al., 2010, 2012; Barnes, 2008). Furthermore, Winges and Soechting (2011) demonstrated that adults' saccades and smooth pursuit anticipated object's new trajectory after a bounce. Von Hofsten et al. (2007) argued that 4-month-old infants' representation of occluded motion goes beyond the representation of simple motion properties such as object speed or occluder width. An evidence of early development of complex physics-based predictions and a resulting facilitation of object tracking would support the account by Balkenius and Johansson (2007). According to this account, infants should be able to anticipate any type of motion assuming that they had sufficient exposure to it. We further suggest that if 5-month old infants had sufficient exposure to circular motion to manage its anticipatory tracking (Gredebäck et al., 2005) they should have also had sufficient exposure to bouncing motions, because these are, in our opinion, more frequently observed by young infants than circular motion. Therefore the current study investigates tracking of bounces with 4- to 10-month-old infants. The selected age range matches the age range selected in studies of anticipatory tracking of circular motion (Gredebäck et al., 2005; Grönqvist et al., 2006).

Second, to our knowledge Kochukhova and Gredebäck (2007) is the only study to demonstrate anticipatory looking when viewing novel nonlinear motion. Kochukhova and Gredebäck (2007) argued for the use of novel nonlinear motion by pointing out that without such a stimulus, one cannot exclude the possibility that infants linearly extrapolate the observed trajectory to anticipate future trajectory. Their argument can be seen as a further elaboration of our first point, and an invastigation with novel motions would provide a further test of the account by Balkenius and Johansson (2007). Therefore, current study additionally investigated whether infants can learn to predict novel trajectories of bounces that are inconsistent with Newtonian physics. We also included *inverse bounce*, where the trajectory after a bounce was the inverse of the trajectory before the bounce, and *perpendicular bounce*, where the angle between the old trajectory and the new trajectory was always 90°.

Third, occlusion or brief disappearance of a moving stimulus has been used to demonstrate anticipatory object tracking in 2 to 9-month-old infants (Gredebäck et al., 2002; Johnson et al., 2003; Kochukhova & Gredebäck, 2007; Rosander & von Hofsten, 2004). In cases of successful anticipation following a disappearance of a slow object, observers move their gaze to where they expect the object to reappear. The observer's gaze lingers there until the object reappears. Thus, the studies with occluded stimulus require infants to make accurate position predictions, but provide only a weak test of their temporal accuracy. However, development of temporal accuracy plays an important role in theories of development of object tracking. Balkenius and Johansson (2007) assumes that accurate anticipation leads to accurate positional as well as temporal control of saccades and of smooth pursuit. In contrast there is some evidence that 2-month-old infants anticipate when a trajectory change will occur, but not what the new trajectory would be after that change (Von Hofsten, 2004). An observation of anticipatory saccades accompanied by reactive smooth pursuit would require a modification of the account by Balkenius and Johansson (2007). Furthermore, due to the weak constraints on temporal accuracy in studies with occlusion, it is not clear whether the anticipatory saccades are catch-up saccades (which are part of object tracking) or whether the anticipatory saccades mark volitional shifts of attention. For the purpose of demonstrating anticipatory looking, the temporal accuracy may not be relevant, but its quantification would be useful in order to evaluate theories of development of object tracking. Therefore, in current study, occlusion was not used and we used two measures of tracking performance that separately assess the positional and the temporal accuracy during free viewing of bounces. Similar to Winges and Soechting (2011) we evaluated the mean *anticipated angle*, which is the angle between the infant's saccade target and the circle's old trajectory with the bounce location at the pivot (see Fig. 1 and compare to "Eye direction" in Figure 6 in their study). Similar to Winges and Soechting (2011) the angle of incidence was varied for this purpose. Bounces with angles of incidence of 0°, 12°, 45° were shown to the infants. In combination with the three bounce laws (physical, inverse and perpendicular), these angles resulted in seven unique *bounce types*. Accurate angle anticipation is independent of timing and ensures that the saccade target will intercept the new trajectory. In addition, in order to intercept the new trajectory at the correct time, the saccade target must match the circle's distance from where the bounce occurred. To account for this, the displacement of saccade targets from the circle along the direction of the circle's new trajectory was evaluated and will be referred to as *motion-parallel displacement* in this report. Assuming that infants accurately anticipated the angle of the object's new trajectory, the temporal accuracy can be evaluated as the lag between the time when the saccade ended and the time of object's arrival at the saccade target location. This timelag can be obtained by dividing motion parallel displacement by object speed. For the purpose of evaluating the temporal accuracy of saccades, object speed was varied between 5°/s and 40°/s, which is the typical speed range covered by studies on infant object tracking (Jacobs et al., 1997; Phillips et al., 1997; Von Hofsten & Rosander, 1996).

Fourth, although saccade frequency is routinely reported, only few studies have described the performance of saccades (e.g. their timelag or accuracy) during object tracking (Gredebäck et al., 2005; Grönqvist et al., 2006). Routinely, either the performance of smooth pursuit or the combined performance of saccades and smooth pursuit is reported. Balkenius and Johansson (2007) assume that catch-up saccades and smooth pursuit rely on predictions of the same anticipatory mechanism. Although the predictions of the anticipatory mechanism are immediately available for saccade control, control of smooth pursuit may require additional practice in order to adapt the parameters of the pursuit mechanism. In a study with novel motion types, it is reasonable to focus on catch-up saccades rather than on pursuit. A failure to demonstrate anticipatory pursuit cannot be unequivocally attributed to failed anticipation, but absence of anticipatory catch-up saccades would imply failed anticipation according to the model by Balkenius and Johansson (2007). Also from the perspective of the account by Rosander (2007), it may be advantageous to focus on catch-up saccades, as the development of saccade control is completed by the 2 months of age, but the development of pursuit control extends beyond 4 months of age so that a failure by 4-month-old infants to show anticipatory pursuit could be attributed to an ongoing oculomotor development. To avoid these ambiguities and to fill the research gap, current study focused on anticipatory saccades. In particular, we focused on catch-up saccades that started before the circle had hit the barrier and that ended after the circle had hit the barrier. For the purpose of the present report, these were referred to as *bounce saccades*. Catch-up saccades that infants made while tracking the object, but not during its bounce were labeled *linear-motion saccades*. Linear-motion saccades were also examined in order to distinguish between potential properties of saccades that uniquely accompany a bounce and those that do not. A timelag of 150 ms and less is commonly used as a threshold in order to identify anticipatory saccades in infant studies (Haith et al., 1988; Johnson et al., 2003; Rosander & von Hofsten, 2004). Even in trained adults it is rare to observe faster reactive saccades (Barnes, 2011). Assuming that an object moves with at 20°/s from left to right, the aforementioned timelag threshold would dictate that a saccade can be classified as anticipatory if it occurs no further than $0.15 \times 20 = 3°$ to the right of the object (i.e., behind the object) and if the vertical distance is close to zero. Consequently, if anticipated angle is accurate, it is possible to additionally distinguish between anticipatory and reactive saccades using motion-parallel displacement estimated in current study. If infants make anticipatory saccades, mean displacement should be less than 0.75° when the circle moves at 5°/s (lower speed limit in current study) and less than 6° when the circle moves at 40°/s (upper speed limit). Similar to previous infant studies (Gredebäck et al., 2002, 2005; Grönqvist et al., 2006), saccade amplitude and saccade frequency were also evaluated. The model by Balkenius and Johansson (2007) predicts that saccade frequency should increase before or during abrupt trajectory changes, i.e. during bounce. Such a claim assumes that infants make anticipatory saccades. If infants make reactive saccades their frequency should increase 200 ms after the bounce and later. According to Balkenius and Johansson (2007), reactive catch-up saccades could be triggered by a large tracking error. Saccade amplitude is indicative of tracking error prior to its onset, because longer saccades are needed in order to rectify larger tracking errors. If bounce saccades are anticipatory rather than

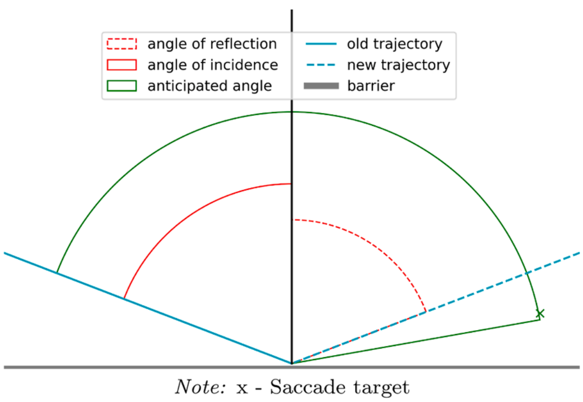

Fig. 1. Vocabulary of a bounce.

reactive, their amplitude should be similar to the amplitude of other anticipatory saccades (assuming similar object speed). To test this claim, the amplitude of bounce saccades was compared to the amplitude of linear-motion saccades and to amplitude of anticipatory saccades reported in other studies of infant object tracking (Gredebäck et al., 2005; Grönqvist et al., 2006).

In summary, current study aimed to advance the current knowledge of infant object tracking by evaluating the qualitative predictions of the model by Balkenius and Johansson (2007). This model emphasizes the role of anticipatory saccades in the development of object tracking, which is also consistent with theories of adult object tracking (Barnes, 2008; Orban de Xivry & Lefevre, 2007). Research with adults has demonstrated their anticipatory tracking of bouncing objects by manipulating the angle of incidence of the tracked object (Winges & Soechting, 2011). A similar study is missing in infant literature but would be of interest because infants should gain exposure to bouncing motion at an early age and should therefore (according to Balkenius & Johansson, 2007) show early anticipatory saccades when tracking bounces. The literature is also missing demonstrations of anticipatory tracking of novel repetitive trajectories. Studies demonstrated that 6-month-old infants require only a few trials to learn the regularities of a novel repetitive motion (Johnson et al., 2003; Kochukhova & Gredebäck, 2007). Therefore, infants should also be able to quickly show anticipatory saccades that would rapidly improve their tracking of novel motions. To test this claim, two novel and physically implausible bounce laws (inverse and perpendicular) were added in current study. The three bounce types and the four angles of incidence resulted in seven unique bounce types that were shown to infants in current study. Depending on whether infants utilize anticipatory or reactive saccades to track bounce, the model by Balkenius and Johansson (2007) makes different predictions regarding the positional and temporal accuracy of these saccades and regarding the saccade-triggering mechanism. Anticipated angle, motion-parallel displacement, frequency, and amplitude of bounce and of linear-motion saccades were analyzed in current study in order to test these predictions.

2. Method

2.1. Participants

Contact data of families were obtained from the local registry office. The families were contacted and invited to participate in current study. Interested families were invited to visit the developmental psychology lab, when the child was approximately 4, 7 and 10 months old. A total of 399 experiment sessions were performed, with 145, 130 and 124 experiment sessions at roughly at the age of 4, 7 and 10 months respectively. A total of 235 infants (108 girls) participated in the experiment sessions. 80 infants participated twice and 42 participated thrice. Earlier studies in our lab showed that participants mostly come from educated and upper-middle-class families. The Ethics committee of the research institution declared the reported study as ethically not problematic. The participation was voluntary and each family received a small present for their participation. Written consent was obtained from the care taker prior to each experimental session. For 376 of the experimental sessions, the care takers agreed with data publication. The raw eye-tracking data along with the code used to run the experiment and the code used to analyze the data is available from https://github.com/simkovic/bounceSac.

2.2. Material and apparatus

The infants were seated and strapped in a highchair for babies. Most of the 4-month-old infants could not sit upright in the highchair and were placed in caregiver's lap. The position of the highchair or the caregiver's chair were adjusted so that infant's eyes were located roughly 60 cm from computer screen, which was the distance recommended by eye-tracker manufacturer. Note that the retinal size of stimulus depended eye-to-screen distance which was affected by infant's movement throughout the experiment session. The values in degrees of visual angle that describe stimulus shape and its trajectory assume a constant eye-to-screen distance of 60 cm. Once infant's eyes were located in a suitable position, caregiver, who stayed in the room during the experiment session, was given a signal to stay quiet and experiment presentation started on monitor screen.

Up to 5 blocks were shown to each infant. Each block consisted of 5 trials. Before each trial, a rotating spiral accompanied by a sound appeared at the center of the screen. Its purpose was to direct infant's attention to screen. The spiral disappeared once the distance between infant's gaze and screen center was less than 18°.

Once infant was looking at the screen, stimulus presentation started. Similar to study by Winges and Soechting (2011), bounces of an object moving with a constant speed were shown from a top-down perspective. Because the type of launching was found to affect infants' predictive performance (Green et al., 2014), we avoided a repeated presentation of an object that was launched from the same position (as was done in Winges & Soechting, 2011) and instead showed on each trial a 10-s-long motion that displayed numerous bounces against boundaries formed by the edges of the computer screen. Presentation of a continuous motion with multiple inflections is common in infant studies of object tracking (e.g. Gredebäck et al., 2006; Von Hofsten & Rosander, 1997). In particular, a white circular disc (1.17° diameter) appeared at the center of the computer screen. Circle immediately started moving with constant speed within an area delineated by screen edges. This area was a rectangle of a size of $37.3 \times 21°$. A bounce occurred when circle's edge touched screen edge. Apart from bounces there were no trajectory changes throughout the trial. The rectangular monitor edge was covered by a cardboard that was vested in a black matte cloth and was ca. 6° wide. Circle moved on a gray background. Each trial lasted 10 s. An empty gray screen was shown for a duration of 800 ms between two consecutive trials. After the first three blocks there was a break of 1–3 min. Additional breaks between blocks were made, if the infant got fuzzy. A calibration routine with nine targets was presented at the end of the experiment session.

Bounce type and initial angle of incidence was varied across blocks. Infants were randomly assigned to one of 5 groups (Group 1–5).

Circle's motion trajectory shown to each group and in each block is shown in Fig. 2. For instance, infants in Group 1, Block 1 watched a horizontal motion from center to right, then to left, then back to right and so forth. As described in introduction, three different bounce types were shown: physical bounce (e.g. Group 3, Block 1), inverse bounce (e.g. Group 2, Block 1), and perpendicular bounce (e.g. Group 4, Block 1). Initial angle of incidence was 0° (e.g. Group 1, Block 1), 12° (e.g. Group 2, Block 1) or 45° (e.g. Group 2, Block 2). Only seven unique bounces were obtained by combining the three selected bounce laws with the three selected initial angles of incidence. For instance an angle of incidence of 45° yielded the same trajectory when it was combined with the perpendicular as when it was combined with the physical bounce law. All subsequent bounces retained the initial angle of incidence. Only exception was physical bounce with 12-° angle of incidence (e.g. Group 5, Block 1) which introduced an angle of incidence of 78°. Summary of the properties of the seven unique bounce types are listed in the seven bottom-most rows of Table 1. Examples of trajectories are shown in Fig. 2.

Blocks alternated between bounce laws and between angles of incidence and groups balanced these alternation so that bounce types were uniformly distributed across groups and across blocks. The goal of such between-block changes was to investigate the speed of adaptation of the anticipatory mechanism. With angle of incidence of 0° (0-physical bounce) it was not possible to create a distinct valid trajectory with another of the two bounce laws. For this reason 0-physical bounces were not counterbalanced across groups or across blocks. Because trajectory changes similar to those created by 0-physical bounce have featured prominently in previous infant studies of object tracking (Von Hofsten & Rosander, 1997, e.g.), we did not want to omit blocks with 0-physical bounces.

Trials within each block showed the same bounce type and circle's initial direction was also the same. Circle's speed was varied across trials within a block. In Group 1, speed was determined adaptively for each trial, based on infant's tracking capability demonstrated on previous trial within the same block. Speed varied between 5 and 40°/s. The initial speed was 15°/s. With the adaptive procedure, most infant's quickly reached the highest speed. To make speed selection more heterogeneous, this procedure was replaced by a fixed speed schedule in the remaining four groups. In particular, speed on trial 1–5 was 21, 7, 28, 35 and 14°/s respectively.

2.3. Data analyses

Infants' point-of-gaze data on screen were measured with a SMI REDn remote eye-tracker that was run at 60 Hz in binocular mode. Saccades were extracted with REMODNAV software (Dar et al., 2021) and this procedure including the preprocessing steps is described in detail in Supplemental material 1. In order to select saccades during which infants were tracking the object, only saccades with a distance between saccade target and circle location of less than 7° were selected. Saccades were divided into two categories that were analyzed separately. The first category consisted of saccades that occurred when circle hit the barrier and changed its path. These were labeled *bounce saccades*. A bounce saccade started before bounce, or up to 150 ms after the bounce and it ended after the bounce. The reasoning behind this choice was that infants' processing and reaction to a motion change would take at least 150 ms and thus eye movements within this time window must be attributed to infants' bounce anticipation. A total of 2733 bounce saccades were

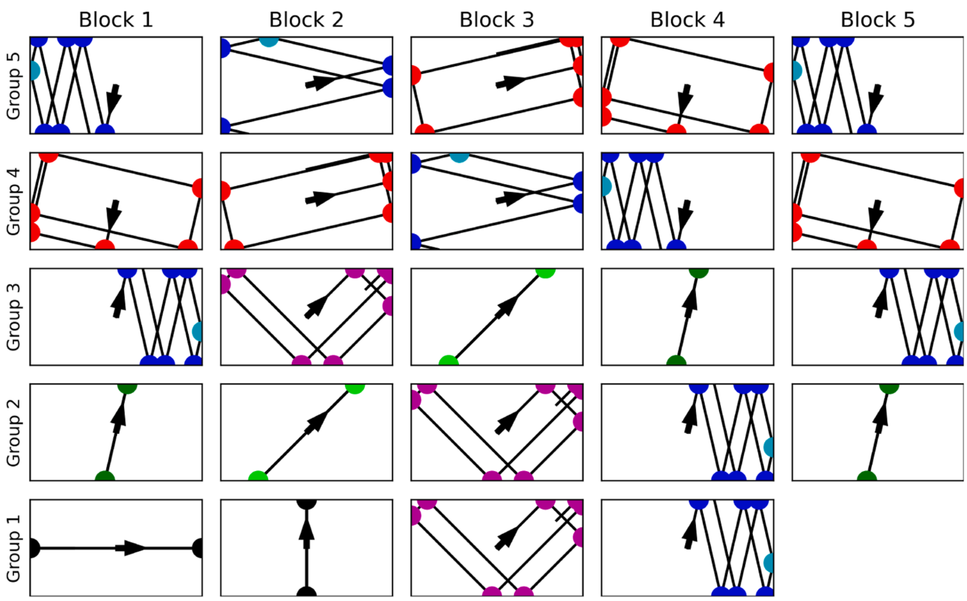

Fig. 2. Circle's trajectory. *Note:* Trajectory (black line) of the circle on the computer screen on a trial during which circle's speed was 20°/s. Each panel shows a trajectory that was presented during a different experiment sessions (in rows) as part of each consecutive block (in columns). The circle always started at the screen center and its initial direction is indicated by the black arrow. Semicircles show bounce locations. The bounce type is indicated by the semicircle's color. The bounce-type-color correspondence is listed in the first four columns of Table 1. Note that in the case of inverse bounce types, the consecutive bounce locations overlap and are therefore not visible.

Table 1
Number of saccades and statistics of circle's speed.

BL	AoI	Bounce type	Color	# Sacs	Mean S	Std S	# Inf
		LM Sac.	–	11,601	21.9	10.9	399
		Bounce Sac.	–	2733	28.3	10.3	355
P, I	0	0-physical	Black	546	34.9	11.1	70
P	12	12-physical	Blue	775	27.1	9.1	233
P, R	45	45-physical	Magenta	418	29.5	11.0	116
P	78	78-physical	Cyan	148	23.8	9.1	104
I	45	45-inverse	Lime	99	26.0	8.6	39
I	12	12-inverse	Green	163	26.1	7.5	54
R	12	12-perpendicular	Red	584	25.1	8.6	168

Note: BL = bounce law; AoI = angle of incidence in degrees; # Sacs = number of saccades; S = speed in °/s; Std = standard deviation; # Inf = number of infants who contributed saccades; P = physical bounce; I = inverse bounce; R = perpendicular bounce.

identified. The second category consisted of 11,601 saccades that occurred while circle followed a linear trajectory. These were labeled *linear-motion* saccades. Saccades that stretched over more than one bounce event were completely excluded from the analyses.

Statistical analysis followed a hierarchical regression approach as recommended by Gelman and Hill (2006). In particular, regression parameters were assumed to vary across infants, implying a hierarchical structure with two levels: saccade level and infant level. Saccade target was the saccade-level outcome variable and speed was included as a continuous linear saccade-level predictor. Age was included as a continuous linear infant-level predictor. The purpose of this hierarchical structure was to avoid a bias due to the unequal distribution of the saccades across infants and the unequal distribution of infants across bounce types. In a hierarchical model, such a bias is avoided by weighting the evidence from each infant's measurements by infant's accuracy and by the number of samples from that infant (Gelman, 2006). The unequal distribution of saccades and of infants across bounce types can be observed in Table 1 and was an unavoidable consequence of circle's uninterrupted movement within a rectangular area which determined the frequency of bounce types. To illustrate this point, one may compare the frequency of cyan and blue semicircles in Fig. 2.

To account for a possible heteroscedasticity, a separate standard-deviation parameter was estimated for each infant. These parameters were partially pooled with a hierarchical structure. An additional parameter was included to estimate the linear effect of age on the standard deviation.

Van Renswoude et al. (2019) showed that during free viewing of visual stimuli that were presented on a computer screen, infants make exploratory saccades directed toward the center of the screen. Such exploratory saccades are not part of object tracking but, because the new trajectory is approximately directed towards the center of the screen, it is possible that some of these exploratory saccades were erroneously misclassified as bounce saccades in current study. The statistical analyses accounted for this possibility by including the direction of the screen center as a linear saccade-level predictor.

2.3.1. *Anticipated angle*

To estimate anticipated angle, circle's location and saccade target of bounce saccades were rotated and shifted such that the incident trajectory and the bounce location coincided across all bounces. This transformation translates saccade targets into coordinate system that was used to report "path of smooth pursuit" in Winges and Soechting (2011, Fig. 2). Parameters of the aforementioned regression model were estimated with the transformed saccade targets. The parameters were then used to estimate mean saccade targets for each bounce type as a linear function of speed and age. Anticipated angle was computed with two-argument inverse tangent function based on the coordinates of mean saccade targets. As a consequence, anticipated angle was determined for each bounce type as a function of speed and age. The transformation and the computation of mean saccade targets is described in detail in Supplemental material 2.1. Values of anticipated angle close to 0° indicate that mean saccade target was located close to circle's old trajectory. On the other hand, values close to 180° would indicate that infants anticipated that circle would cross screen boundary and continue moving along its old trajectory.

2.3.2. *Motion-parallel displacement*

Regression analysis was repeated with bounce-saccade targets that were rotated and shifted such that circle's position was at the origin and the direction of circle's direction was aligned with negative direction of horizontal axis. In this coordinate system, the horizontal coordinate of the mean saccade target corresponded to motion-parallel displacement. Values close to zero marked a precise anticipation. A positive value indicated that saccades landed behind circle. A negative value indicated that saccades landed in front of circle. Motion-parallel displacement of linear-motion saccades was estimated in similar fashion with an additional regression analysis.

2.3.3. *Saccade amplitude*

Regression analysis was adapted to estimate saccade amplitude of bounce and linear-motion saccades. In these analyses, the outcome was saccade amplitude, which was the distance (in degrees) between the location of gaze when saccade started and the location of gaze when saccade ended.

3. Results

3.1. Bounce saccades

Estimates of anticipated angles assuming that infant was 7 months old are shown in Fig. 3 A for each bounce type. Each full line with an 95 % band shows (from left to right) how anticipated angle changed as circle's speed increased (from 5°/s to 40°/s). With increasing speed the difference between anticipated angle and the angle of circle's direction after the bounce (dashed line) got smaller. With exception of 45-physical bounce type, this difference was less than 15° when circle moved at 40°/s. In the case of 45-physical and 12-perpendicular bounce anticipated angle deviated notably from angle of circle's direction and this was the case even at 40°/s. The width of 95 % band decreased with greater speed. The 95 % band showed that deviations in following cases cannot be attributed to

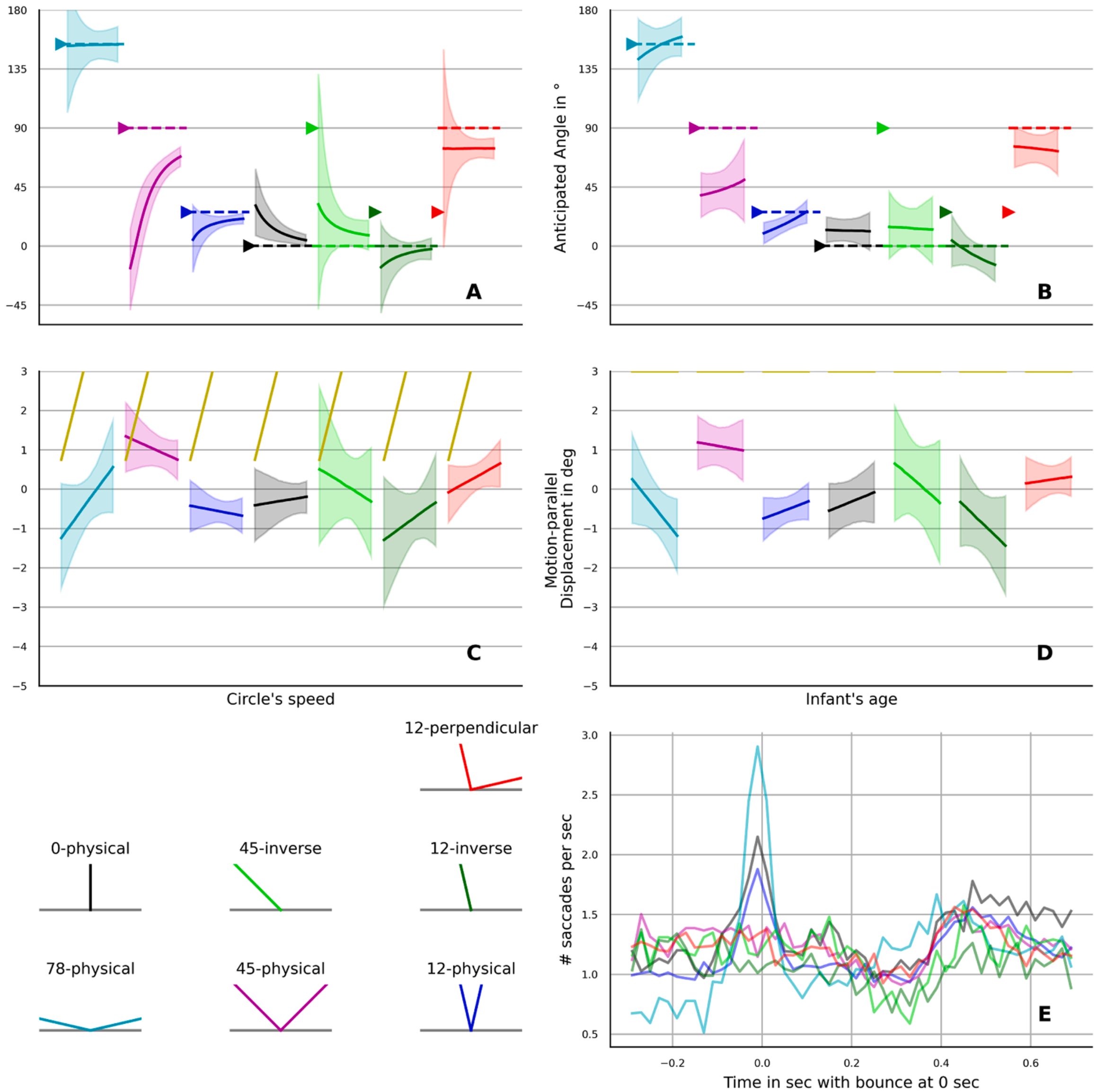

Fig. 3. Estimates of anticipated angle and motion-parallel displacement. *Note:* Panel A: Anticipated angle in ° assuming that infant was 7 months old. Each full line shows change in median estimate that followed a change in speed from 5°/s (left end) to 40°/s (right end). Each colored segment in Panels A–D shows the corresponding 95 % uncertainty band. Dotted lines in Panel A and B show the angle between circle's old and new direction. The angle predicted by Newtonian physics is shown by triangle. Panel B: Anticipated angle in ° assuming that circle moved with a speed of 20°/s. Each full line shows the change in median estimate that followed a change in infant's from 4 months (left end) to 10 months (right end). Panels C and D show motion-parallel displacement respectively as a function of circle's speed and of infant's age. Layout of these panels is similar to layout of panel A. Yellow lines show maximum value consistent with a timelag smaller than 150 ms. Panel E: Saccade frequency relative to bounce at 0. Frequency was computed as the number of saccades per second.

sampling error: 45-physical bounce, 12-physical bounce at speed greater than 10.6°/s, 0-physical bounce, 45-inverse bounce at speed from 21.1 to 30.2°/s, and 12-perpendicular bounce at speed greater than 15.5°/s.

Next, the impact of three types of bounce representation on anticipated angle is considered in detail. We consider whether infants anticipated the bounce that was shown (marked by a dashed line in Fig. 3 A), a physical bounce (marked by a triangle) or no bounce at all (angle equal to). Note that only results from inverse or perpendicular bounces are relevant for the purpose of distinguishing between the first two representations. Irrespective of speed, when inverse or perpendicular bounce was shown, anticipated angle was closer to angle of circle's direction than to angle predicted by physics. Furthermore, apart from 45-inverse bounce at less than 8.15°/s and 12-perpendicular bounce at less than 7.45°/s, differences between angle of circle's direction and angle predicted by physics could not be attributed to sampling error. In the aforementioned two cases, 95 % band was too wide to favor any conclusions regarding anticipated angle and the type of infants' bounce representation. The assumption that infants do not anticipate a bounce and that they expect circle to cross screen edge and to continue moving along its old trajectory leads to the prediction that infants would exhibit an anticipated angle of 180°. Apart from 78-physical bounce at low speed, this prediction was not consistent with anticipated angle observed in current study.

The estimates of anticipated angle assuming that circle moved at a speed of 20°/s are shown in Fig. 3 B for each bounce type. Each full line with a 95 % band shows (from left to right) how anticipated angles changed as infants grew older (from 4 to 10 months of age). In the case of 45-physical and 12-physical bounces, anticipated angles got closer to the angle of circle's direction as age increased. In contrast, in case of 12-inverse bounce, the difference between the two angles increased with age. Note that in this case the difference between the angle of circle's direction and the angle predicted by physics also increased. In the case of the remaining bounce types, there was no clear effect of age. Similar to the estimates of anticipated angle in Fig. 3 A, the estimates in Fig. 3 B also suggested that infants' saccades anticipated angle of circle's direction rather than angle predicted by physics. This balance of evidence did not change with age.

Motion-parallel displacement when infant was 7 months old is shown in Fig. 3 C for each bounce type. Each full line with an 95 % band shows (from left to right) how motion-parallel displacement changed as circle's speed increased (from 5°/s to 40°/s). Fig. 3 D shows motion-parallel displacement of saccades as a function of infant's age assuming that circle's speed was 20°/s. Yellow lines show maximum value consistent with a timelag smaller than 150 ms, which in turn is commonly used as a criterion of anticipatory saccades. Median estimates of motion-parallel displacement were smaller than the threshold value, which suggests that infants made predictive saccades. The case of 45-physical bounce at speed smaller than 12.5°/s and the case of 45-inverse bounce at speed smaller than 12.35°/s were the only cases in which confidence bounds included possibility of reactive saccades.

When comparing 95 % intervals of motion-parallel displacement between different speed values in Fig. 3 C and between different age values in Fig. 3 D we found that 95 % intervals always overlapped. If we take overlapping 95 % intervals as indicator of statistical significance (Cumming & Finch, 2005; Knol et al., 2011), then speed and age did not affect motion-parallel displacement. The same can be said about the effect of speed and age on anticipated angle. Only exception was the 95 % interval of anticipated angle associated with 45-physical bounce which shifted considerably with speed.

Saccade amplitude at 7 months of age and when circle moved with 20°/s was 5.37° (95 % interval $[5.08, 5.66]$). Saccade amplitude decreased with age by 0.19° per month (95 % interval $[0.08, 0.29]$). Saccade amplitude increased by 1.44° per 10°/s increase in speed (95 % interval $[1.25, 1.62]$).

Saccade frequency relative to time of bounce is shown in Fig. 3 E. The Bernoulli-distribution-based confidence interval (see Example 6.17 in Wasserman, 2004) was less than $\mp$ 0.05 across all bounce types and all time points. The saccade frequency showed a peak at the time when bounce took place, but only in the case of 0-physical, 12-physical or 78-physical bounce. A slight increase in saccade frequency observed 400–600 ms after the bounce.

3.2. Linear-motion saccades

Assuming that circle moved with 20°/s and that infant was 7-month-old, motion-parallel displacement was − 0.38° (95 % interval $[-0.52, -0.23]$). Motion-parallel displacement decreased by 0.12° per month (95 % interval $[0.06, 0.18]$). Motion-parallel displacement increased by 0.052° per 1 °/s increase in speed (95 % interval $[0.046, 0.058]$) implying that saccades landed at a location farther behind the circle when circle's speed increased. These values suggest that the largest motion-parallel displacement of linear-motion saccades would occur when 4-month-old infants watched the fastest (40°/s) bounces. In this case, the aforementioned parameter estimates implied a motion-parallel displacement of 1.02°, which was safely below the threshold for anticipatory saccades of 6°. Thus, motion-parallel displacement suggested that linear-motion saccades were anticipatory irrespective of age and speed.

Amplitude of linear-motion saccades at 7 months of age and when circle moved with 20°/s was 5.59° (95 % interval $[5.41, 5.77]$). Saccade amplitude decreased with age by 0.05° per month (95 % interval $[-0.02, 0.13]$). Saccade amplitude increased by 1.13° per 10°/s increase in speed (95 % interval $[1.04, 1.21]$).

3.3. Supplemental analyses

As part of the aforementioned analyses, mean saccade targets had been estimated in order to compute anticipated angle. Estimates of mean saccade target. al.ng with estimates of the corresponding regression coefficients are presented in Supplemental material 3. These estimates further confirm the results obtained with anticipated angle and with motion-parallel displacement. These analyses showed that the decreasing difference between anticipated angle and angle of circle's direction can be attributed to a motion-perpendicular displacement that was independent of speed. The speed-dependent component (indicated by regression coefficients) showed motion-perpendicular displacement only in the case of 12-perpendicular bounce.

4. Discussion

The analyses of anticipated angle, motion-parallel displacement, saccade frequency, and amplitude support the overall conclusion that infants made anticipatory saccades while tracking a bouncing object. Furthermore, the properties of anticipatory saccades were broadly consistent with the predictions of the developmental model of object tracking by Balkenius and Johansson (2007). In particular, motion-parallel displacement of infants' saccades was close to zero, which suggests that infants used saccades to position their gaze at the circle's location. The effect of speed on motion-parallel displacement of bounce saccades (as indicated in Fig. 3 C but also in the supplemental analyses) was close to zero suggesting that infants' bounce saccades correctly accounted for object speed. Estimates of anticipated angle in the cases of inverse and perpendicular bounce types were not consistent with the claim that infants' bounce saccades anticipated physical bounces or that they did not anticipate the bounce. Instead, the most likely explanation was that infants learned to anticipate the direction of the circle's new trajectory after observing few bounces. There was an unequivocal evidence that linear-motion saccades were anticipatory. The close match between linear-motion and bounce saccades in terms of their amplitude and motion-parallel displacement further supports the conclusion that bounce saccades were also anticipatory. Another piece of supporting evidence was provided by the observation that for some bounce types, the peak of saccade frequency coincided with the time of bounce. In Section 4.1, we further show that the reported displacement, amplitude and frequency of bounce saccades was also consistent with estimates reported by other studies that found anticipatory saccades.

We also found that infants' bounce saccades did not always correctly anticipate the angle of circle's direction, and we also found few cases in which estimates of motion-parallel displacement did not exclude the possibility of reactive saccades. In other cases, saccade target was in front of the circle, which may also put the temporal accuracy of infants' anticipation in question. In addition, saccade frequency of inverse and perpendicular bounces did not show a peak at the time of bounce, and there was a small increase in saccade frequency 400–600 ms after the bounce, which could be interpreted as an evidence of reactive saccades. At first glance, these numerous deviations from accurate tracking might suggest that infants did not make anticipatory saccades, or at least that not all infants and not under all circumstances did so. As already mentioned in the introduction, the purpose of catch-up saccades is, according to Balkenius and Johansson (2007), not to accurately transport the point of gaze to the location of the tracked object. Rather, the purpose of catch-up saccades is to bring gaze to a suitable position at an opportune time to resume smooth pursuit. Furthermore, according to Balkenius and Johansson (2007), anticipatory saccades may be initiated by an anticipation of an event (i.e. bounce), but their initiation is also affected by the (anticipated) tracking error. Both mechanisms could affect the reported frequency of saccades. A detailed discussion of how and to what extent the apparent inaccuracies can be accounted for by current theories of infant object tracking is provided in Section 4.2.

4.1. Amplitude, frequency and displacement of anticipatory saccades in studies with infants

Similar to current study, Phillips et al. (1997) and Von Hofsten and Rosander (1997) found that the saccade amplitude increased with stimulus speed and decreased with age. On the other hand, Richards and Holley (1999) reported a decrease in the saccade amplitude with age but no effect of the target speed. Phillips et al. (1997) reported a mean saccade amplitude of ca. 6° for 4-month-old infants viewing a horizontal triangular motion with 24°/s speed, while Von Hofsten and Rosander (1997) reported 6.3° for 5-month-old infants viewing a horizontal triangular motion with 20°/s speed. Based on the regression models obtained in current study, the corresponding saccade amplitude estimates would be 6.2° and 5.7° respectively in case of linear-motion saccades and 6.5° and 5.7° in case of bounce saccades. Thus, current estimates were slightly larger than in the study by Von Hofsten and Rosander (1997), but similar to those in Phillips et al. (1997).

The saccade frequency in Fig. 3 E was, with exception of the peaks at the time of bounce, similar to that reported in other studies (Gredebäck et al., 2005; Phillips et al., 1997; Rosander & von Hofsten, 2002; Von Hofsten & Rosander, 1997). The sharp peaks of saccade frequency around the time of the bounce provide some justification for the focus on bounce saccades and for the time window that was used to select them.

Instead of displacement, previous studies of infants' tracking of circular motion (Gredebäck et al., 2002, 2005; Grönqvist et al., 2006) reported tracking accuracy that was measured as the average gaze-target distance. The reported accuracy was 1–3°, which is not consistent with a zero or with a negative motion-parallel displacement. The aforementioned studies furthermore reported notable effects of speed and of age on the gaze-target distance. We suggest two reasons why the gaze-target distance should not be compared with motion-parallel displacement. First, computation of the gaze-target distance in these studies included both saccades and smooth pursuit. The notable gaze-target distance may then reflect the poor gain of smooth pursuit and may obfuscate accurate saccades. Second, from a statistical perspective a mean distance will be larger than a mean displacement of the same random variable. This is because distance is always positive, but displacement can be both positive and negative. Positive and negative deviations from the mean saccade target that arise due to measurement error cancel out when the mean displacement or mean timelag is computed, but they accumulate when the mean distance is computed (see also the discussion of this issue in Bronson, 1990). It is therefore better to compare displacement with timelag.

As already mentioned in the introduction, timelag can be obtained by dividing motion-parallel displacement by the circle's speed. Because object speed did not affect motion-parallel displacement of bounce saccades, we refrained from reporting timelag as this would create a spurious correlation between timelag and object speed and any other variables associated with object speed. For the purpose of comparison with published timelag estimates, we note that (assuming a speed of 20°/s and an age of 7 months) the reported displacement of linear-motion saccades corresponded to a timelag of − 19 ms and that the timelag of bounce saccades varied between − 70 and 70 ms across all bounce types. In their study with 6-month-old infants who watched circular motion, Gredebäck et al. (2005) reported that timelag of saccades was close to zero and that in some age-speed constellations the saccade targets even preceded the tracked object (i.e. timelag was negative). Their results are consistent with the estimates of motion-parallel displacement reported in current study. Furthermore, in Gredebäck et al. (2005) the saccade timelag was unaffected by speed and age. Current study did not find an effect of age on motion-parallel displacement, but a small speed effect was found with linear-motion saccades. This would correspond to an increase in timelag of 2.5 ms per 1°/s increase in speed. Such a small effect is consistent with the estimates of the speed-dependent change in motion-parallel displacement of bounce saccades and also with the estimates of speed-dependent change in timelag in Gredebäck et al. (2005). We believe that the relatively large number of linear-motion saccades was the main reason why the statistical analyses were able to find a speed effect in the case of linear-motion saccades, but not in the other two aforementioned cases.

In contrast to Gredebäck et al. (2005), Grönqvist et al. (2006) reported (with 5-month-old infants who watched a circular motion) a timelag of 144 ms and 78 ms on the horizontal and vertical axis, respectively, which is not consistent with current results. The two referenced studies provided conflicting evidence, but reported very similar methodology. As a consequence, we conclude that current timelag estimates are consistent with the estimates in Gredebäck et al. (2005), and that we cannot provide an explanation why the estimates in Grönqvist et al. (2006) differ.

4.2. Apparent inaccuracies

In most cases, anticipated angle was similar to the angle of circle's direction after the bounce. Nevertheless, notable deviations of anticipated angle from the circle's angle were found. Anticipated angle associated with 45-physical, 12-perpendicular and 12-physical bounce was smaller than the angle of circle's direction (see Fig. 3 A). In addition, anticipated angle associated with the 0-physical and 45-inverse bounces was larger than the angle of circle's direction, although in the latter case the difference could have been a consequence of sampling error, which is indicated by the 95 % intervals. It is not possible to offer a single simple explanation that would account for all of the aforementioned differences. Instead a range of potential explanations is presented for consideration by the reader, which may inform future research.

With exception of the 12-perpendicular bounce, the aforementioned differences got smaller as the circle's speed increased. This along with supplemental analyses suggests that speed-independent saccade-target positioning was responsible for the differences between anticipated angle and the angle of circle's direction. What kind of positioning might have been involved? First, one may consider that such positioning might involve a shift against the direction of the old trajectory. This would account for the cases in which anticipated angle was smaller, but it cannot account for the cases in which anticipated angle was larger than the angle of circle's direction.

Second, note that infants required at least one observation of a new bounce law in order to adapt their predictions. Then, one may consider that an inaccurate anticipated angle was a consequence of a delayed adaptation to a bounce-law change. Such bounce-law changes occurred after Block 2 and again after Block 4 (Fig. 2). For instance, infants in Group 5 would anticipate an angle of 24° rather than an angle of 90° during the first couple of bounces shown in Block 3. An angle of 24° would result from physical bounce law and both the physical bounce law and bounces with an angle of 24° between the old and new trajectory were shown in Block 1 and Block 2 to infants in Group 5. An anticipated angle of roughly 80° associated with the 12-perpendicular bounce would then result as a mix of saccades in which the majority had anticipated an angle of 90° and the minority had anticipated angle of 24°. The delayed adaptation of the anticipated angle to a bounce-law change can account for most of the cases in which a difference between anticipated angle and the angle of circle's direction was found. It cannot account for the case of 12-physical bounce, in which the anticipated angle was smaller than the angle of circle's direction. In most cases when blocks with 12-physical bounce followed a bounce-law change, they were preceded by blocks that showed 12-perpendicular bounce. Delayed adaptation would predict an anticipated angle that was larger than the angle of circle's direction, but this was not the case. Furthermore, the delayed adaptation cannot explain the difference observed with the 0-physical bounce, because this bounce type was only presented in Block 1 and Block 2.

Note that Kochukhova and Rosander (2008) demonstrated that infants as young as five months of age require only few trials to predict a reoccurence of an object that was moving along a nonlinear trajectory. Thus, the second explanation is consistent with the account by Balkenius and Johansson (2007). However, the first explanation would require some modifications to the specification of the pursuit component in Balkenius and Johansson (2007). Ferrera and Lisberger (1995) showed that momentum transfer between subsequent smooth-pursuit episodes can occur as part of adults' object tracking. This would suggest that if the infant was pursuing the old trajectory before the bounce saccade, the direction of pursuit after the bounce would partially shift in the direction of the old trajectory, even if this did not match the new trajectory. Anticipatory bounce saccades may compensate for this error by shifting the saccade target against the direction of the old trajectory. However, the aforementioned adult studies investigated smooth-pursuit direction changes that were caused by switching between concurrent targets. It is not clear whether these findings apply to smooth-pursuit direction changes that were caused by an anticipated trajectory change and further research in this direction is needed.

In addition to inaccurate angle anticipation, some cases of positive and negative displacement were also observed. A reader may be surprised by negative motion-parallel displacements, which were observed, for example, in the case of 12-physical bounce type or in the case of linear-motion saccades. However, a similar strategy of positioning gaze in front of the arriving object was observed in Aslin (1981), Von Hofsten and Rosander (1996), and in Von Hofsten and Rosander (1997, who referred to this tracking behavior as "undershooting"). Negative displacement is also consistent with the account by Balkenius and Johansson (2007) according to which the purpose of catch-up saccades is to facilitate the subsequent pursuit. Negative motion-parallel displacement of catch-up saccades offers a time provision to ramp up the speed of smooth-pursuit so that it matches the speed of the approaching object.

Next, consider the cases of bounce saccades with large positive displacement. When the circle was slow, the 95 % interval in Fig. 3 C included the possibility of reactive saccades in the case of 45-physical and 45-inverse bounce type. Note that in these cases there was also a large difference between the anticipated angle and the angle of circle's direction. Therefore we attribute the large motion-parallel displacement in these cases to poor angle anticipation rather than to a frequent use of reactive saccades.

Finally, saccade frequency showed a peak at the time of bounce in the case of 0-physical, 12-physical and 78-physical bounce types and it is unclear why there was no similar increase in frequency for the remaining bounce types. In addition, there was a small increase in saccade frequency from 400–600 ms after the bounce, which was independent of bounce type. This small increase can be interpreted as an evidence for reactive saccades. The delay in the range of 400–600 ms matches the latencies of reactive saccades of 4-month to 10-month-old infants that have been reported by Gredebäck et al. (2006) and Kenward et al. (2017). According to Balkenius and Johansson (2007), reactive saccades are triggered by large tracking errors. In the present case, the large tracking error would be caused by the failure to (correctly) anticipate the bounce. This account can explain the timing of the increase that was observed 400–600 ms after the bounce. It can also explain the broader and flatter distribution of this increase over time compared to the sharp peaks observed at the time of bounce. Anticipatory saccades should be highly temporally contingent on the anticipated event, and such high temporal contingency would result in a narrow saccade distribution across time. Therefore, the narrow peaks probably correspond to a high frequency of anticipatory saccades. According to Balkenius and Johansson (2007), the initiation of anticipatory saccades is also influenced by the tracking error. The cases in which no sharp peak in saccade frequency at the time of bounce occurred, could correspond to cases in which saccades were not necessary and in which the tracking was achieved by smooth pursuit. We cannot offer any explanation why inverse, perpendicular, and 45-physical bounces, but not the remaining bounce types, should be tracked with pursuit. Therefore, the claim that infants performed smooth pursuit during bounce remains speculative. Note, that an increase in saccade frequency from 400–600 ms after the bounce was also observed in the case of 0-physical, 12-physical, and 78-physical bounce types. It is unlikely that infants would make both an anticipatory and a reactive saccade as a response to a bounce. They may make additional reactive saccades to correct for inaccurate anticipatory saccades, but this would imply that the latency of reactive saccades would increase beyond 600 ms. Rather, we think that infants mostly proceeded to track circle with smooth pursuit from 100–400 ms after the bounce, and that the subsequent increase in saccade frequency marks another wave of catch-up saccades that was not directly related to the bounce event.

4.3. Conclusions and outlook

Current study provided evidence that 4-month-old to 10-month-old infants use anticipatory saccades to track bouncing objects. Bounce saccades showed accurate angle anticipation, they anticipated the object's distance from the barrier, and at least for some bounce types, the frequency of saccades increased sharply when the bounce occurred. Notable inaccuracies were observed, which we tried to explain by pointing out that, according to the current theories of object tracking (Balkenius & Johansson, 2007; Barnes, 2008), the role of anticipatory saccades is to support accurate pursuit. Age did not affect anticipated angle or motion-parallel displacement, although small effects (e.g., change in displacement less than 0.02°/month) may be uncovered by future studies that manage to obtain a large number of bounces saccades. The lack of an age effect supports the account of saccade development by Balkenius and Johansson (2007), according to which anticipatory saccades are available to very young infants and their use in object tracking is only contingent on a sufficient exposure to bouncing motion. Furthermore, the fact that infants showed anticipatory saccades when tracking perpendicular and inverse bounces suggests that observing several bounces is sufficient to obtain a motion representation that would facilitate accurate predictions. In future studies, researchers may wish to investigate infants' use of anticipatory saccades when presented with even more complex motion types, such as intentional motion (Gergely & Csibra, 2003) or object collisions that alter object speed. Finally, saccade amplitude, saccade frequency, and motion-parallel displacement did not notably differ between linear-motion and bounce saccades. In Section 4.2, we further showed that the current estimates are also consistent with estimates of saccade amplitude, saccade frequency and timelag from other studies that demonstrated anticipatory saccades with different motion types (Gredebäck et al., 2005; Phillips et al., 1997; Von Hofsten & Rosander, 1997). This agreement suggests that the mechanisms controlling anticipatory saccades are independent of the motion type, which is consistent with the assumptions of the model by Balkenius and Johansson (2007). Current study used gaze-circle distance to identify bounce and linear-motion saccades. Accuracy was also used in the aforementioned studies to exclude episodes in which infants did not track the stimulus. This convergence in tracking-identification methodology may also have contributed to the homogeneity of the reported estimates. In future studies, it would be useful to develop and employ tracking-identification methods that consider sequences of eye movements rather than properties of individual events, such as saccade accuracy.

Section 4.2 raised several issues that could be addressed by investigating how smooth pursuit contributes to tracking of bouncing objects. Although the frequency of saccades at the time of bounce increased in case of some bounce types, in other cases no such increase was observed. We speculated that infants tracked these bounces with pursuit. To evaluate this claim, future research should examine the relative proportion of saccades and smooth pursuit while tracking bounces as a function of speed. Winges and Soechting (2011) reported that adults predominantly used smooth pursuit to track an object moving at 18.2°/s. Evidence of undershooting when infants tracked horizontal direction changes (Von Hofsten & Rosander, 1997) suggests that infants could track slow 0-physical bounces with pursuit. Assuming that infants also employ pursuit to track bounces, investigating how the pursuit's anticipated angle, timelag and gain change with age would provide an interesting test of the pursuit component of the model of development of object tracking by Balkenius and Johansson (2007). Apart from the pursuit that accompanies bounces, in Section 4.2 we suggested that smooth pursuit that precedes or follows bounce saccades may be affected by bounce. In particular, future studies should investigate whether a transfer of momentum between successive pursuit episodes occurs. Such an investigation would clarify the role of the speed-independent component of bounce-saccade targeting that was observed in current study.

Author Statement

Both authors contributed equally to the research project and to the manuscript.

CRediT authorship contribution statement

Birgit Träuble: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Matus Simkovic:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Data availability

The raw eye-tracking data along with the code used to run the experiment and the code used to analyze the data is available from https://github.com/simkovic/bounceSac.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.infbeh.2025.102029.

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