

Frames of reference for anticipatory action in 4-month-old infants

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Abstract

The spatial representations of 4-month-old infants were examined in two experiments using a modified version of the visual expectation paradigm (VExP). The experiments were designed in order to determine what spatial frames of reference were available to infants for making anticipatory saccades. In Experiment 1, we found that infants most often used a retinocentric frame of reference that did not take into account their current eye position in making an anticipatory saccade. However, Experiment 2 revealed that under certain conditions infants are more likely to make anticipatory saccades consistent with a body- or object-centred frame of reference. The main difference between the two experiments was the degree to which the featural properties of the stimuli varied. The results shed light on the development of spatial representations for action in infancy.

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A central question in cognitive development concerns the nature of spatial representations early in life and their patterns of change. Recently, a number of investigators have focused on the frames of reference or coordinate systems that might guide action early in life. While some frames of reference can be extracted directly from sensory signals (e.g., the eye-centred or retinocentric position of a visual target), other higher order frames require the integration of non-visual information about head or body position or even the relative positions of multiple objects in the environment. Thus, changes in frames of reference used in spatial action may index the development of perceptual and cognitive systems that integrate multiple sources of information into a more flexible and unified whole. For this reason it is important to investigate the development of this coordination of spatial frames of reference in infants.

A frame of reference permits the location of various target points to be encoded systematically for use in planning subsequent actions. At a minimum, a frame of reference consists of a point of origin and usually a set of directed axes. For example, when an observer fixates a visual stimulus, she establishes an eye-centred or retinocentric frame of reference at the point of fixation from which the location of other points in the visual field relative to the point of fixation can be determined. Because the eyes move with respect to the head, and the head with respect to the body, the position of a given point in space coded in retinocentric terms changes with each change in eye or head position. Thus, while retinocentric position is specified anatomically by the point-to-point topographic projection from the retina to

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the visual centres of the brain (e.g., Fox, Miezins, Allman, Van Essen, & Raichle, 1987), retinocentric position is not a stable framework for encoding location.

In contrast, encoding a visual target's position with respect to an origin associated with the head or trunk overcomes some of these difficulties. We call head or trunk-centred representations *body-centred* for simplicity. Computing them requires that retinocentric position be combined with eye and head position. Of course, body-centred representations are not completely stable either, as most organisms move through space in carrying out actions. Thus, it is possible to encode spatial position using external landmarks or reference points, sometimes termed *allocentric* reference frames (see Newcombe & Huttenlocher, 2000). In this paper, we focus on the use of representations that are *object-centred*, or based on specific distances and displacements from visible objects in the immediate environment. Research on the spatial frames of reference available to infants has utilised a number of divergent paradigms, and, to some degree, has yielded equally divergent pictures of their spatial abilities. Some experiments have required infants to watch as a toy is hidden in a well on a table before being moved (passively) to the opposite side of the table. The infant was then prompted to reach again for the hidden object. The earliest use of this paradigm showed infants reaching for the object in the same egocentrically determined location rather than the correct location (Bremner, 1978a; Bremner & Bryant, 1977; also see Acredolo, 1978 for a similar method yielding similar results). In the ensuing years, however, the notion of the "egocentric infant" has undergone substantial modification.

For example, Acredolo (1979) showed that when infants were tested in a very familiar environment, they tended to make use of distal landmark cues that they had not been found to use in laboratory settings. In a review, McKenzie (1987) pointed out that spatial egocentrism in infants of 8 months of age tends to be the exception rather than the rule. Specifically, infants ignore landmarks only under certain environmentally unusual conditions. Some of these conditions include: when there are no direct or salient landmarks, when the environment is unfamiliar, when the overall room is circular (i.e., without any geometric cues), and when there are no gravity cues. Research by Kaufman and Needham (1999) revealed that even in unfamiliar environments, if infants are engaged in a task that allows them to attend to the layout of the room (i.e., a dishabituation task that does not force infants to be goal-focused), infants as young as 6 months can keep track of their own passive movements and use their displacement to anticipate the location of a salient object.

While these findings suggest that body- or object-centred representations are available early in infancy, Gilmore and Johnson (1997a, 1997b) have suggested that these higher-order representations emerge gradually from a more primitive, eye-centred or retinocentric frame that characterises spatial perception in the first few months after birth. Gilmore and Johnson examined patterns of saccadic eye movements in 3–7-month-old infants using a behavioural paradigm that permitted responses based on retinocentric representations to be distinguished from those based on body- or object-centred representations. One advantage of eye movement measures is that saccades can be examined in people of all ages beginning with very young infants. This allows for developmental comparisons across a wide age span. Additionally, the relationship between systems that control the overall duration of looking across multiple saccades and fixations and those that control the direction and magnitude of each individual saccade is not well understood. It is possible and perhaps likely that these are related but functionally distinct systems. Because looking-time tasks (such as Kaufman & Needham, 1999) record the former and tasks such as the double-step and visual expectation paradigm (both described below) record the latter, differences in spatial information used in these tasks might be expected to differ.

Gilmore and Johnson (1997a, 1997b) used a double-step saccade paradigm in which infants saw sequences of visual targets that appeared for very brief durations, one after the other (see Fig. 1). These authors observed that younger (3–5-month-old) infants made more retinocentric than body-centred saccade sequences while 6–7-month olds showed the reverse pattern. Because retinocentric position information is specified by the topographic projection from the retina to cortical visual structures that mature early, Gilmore and Johnson theorised that retinocentric representations are the most primitive ones possible, and therefore develop first. Furthermore, because body-centred representations require the systematic integration of visual and non-visual information, Gilmore and Johnson concluded that body-centred representations for action are not present from birth but emerge, probably through experience, over the first few postnatal months.

This conclusion is reminiscent of the early claims by Acredolo and Bremner concerning developmental limits on spatial representations for manual action in older infants. However, like Acredolo and Bremner, it is possible that Gilmore and Johnson underestimated the abilities of young, 3- and 4-month-olds, to use body- or object-centred representations. Thus, it is possible that certain variations in saccade-tracking tasks could reveal more sophisticated or

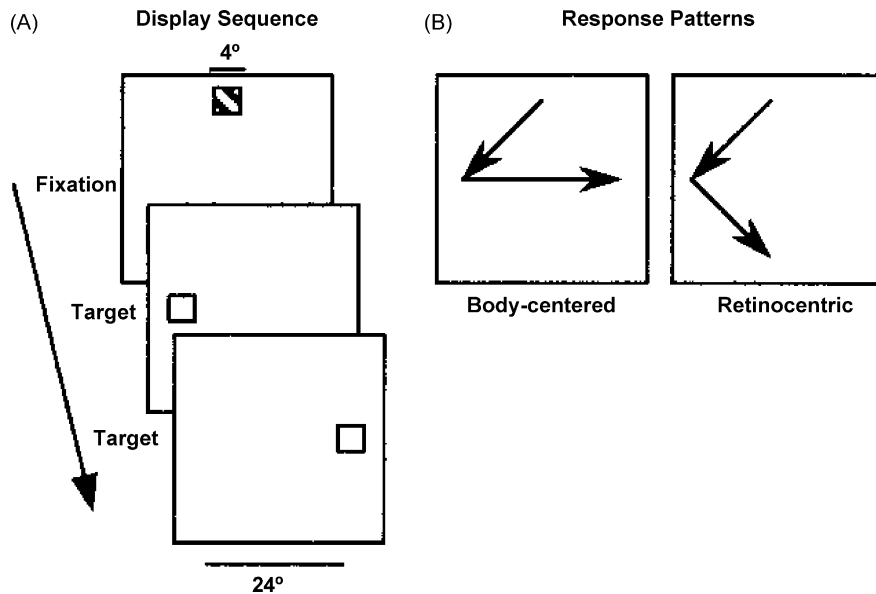


Fig. 1. Design of Gilmore and Johnson (1997a). (A) A trial began with the presentation of a fixation stimulus consisting of a sequence of coloured shapes which was followed by the brief appearance of two identical targets that flashed sequentially. Fixation and target positions varied in a pseudo-random order. (B) Two types of responses were of critical concern: a body-centred sequence consisting of two saccades, the first saccade to the first target, and the second saccade to the second target; a retinocentric sequence consisting of two saccades, the first to the first target, and the second equivalent to the position of the second target relative to the fovea at the time it was initially presented. In the situation depicted here, the second target appeared below and to the right of fixation, so a retinocentric second saccade would be directed below and to the right of the endpoint of the first saccade.

cognitively demanding representational abilities of young infants. The double-step saccade task certainly has limitations, among them are the confound between perceptual and motor representations, and the possibility that the task reveals representations unique to saccade planning under reduced cue conditions. The double-step task as used by Gilmore and Johnson also confounds body-centred and object-relative frames of reference. That is, responses that were coded as body-centred could not be distinguished from target- or screen-relative responses.

If retinocentric representations dominate young infants' eye movement planning, then these may be evident in other tasks. Particularly, anticipatory action may involve the use of more advanced frames of reference. Consequently, the goal of the research presented here was to examine the spatial representations involved in the formation of expectations about the future locations of visual targets.

To do so, we used a variation of the visual expectation paradigm (VExP) designed by Haith, Hazan, and Goodman (1988). The VExP is often used to assess infants' sequence learning abilities. Infants are presented with stimuli that appear sequentially with only one stimulus appearing on the screen at any given time. Generally, researchers using the VExP have been interested in developmental trends in the degree to which infants can anticipate a stimulus presentation as a function of the complexity of the spatiotemporal patterns presented. We were interested in the spatial factors influencing saccades and adjusted the VExP to accomplish this.

We asked the question: what frame or frames of reference do infants use to make anticipatory saccades? During VExP tasks, do infants learn a motor pattern that allows them to accurately move their retina to point to alternating stimuli? Or, are infants making their saccades based on a more sophisticated spatial representation about where flashed targets will appear? Our paradigm attempts to answer this question by occasionally perturbing the normal spatiotemporal sequence with probes placed in different locations, thereby causing infants' to direct their gaze away from the normal alternating sequence. By examining what types of saccades infants make to get back to the original sequence we are able to infer the types of representations that are available to them. Specifically, we asked whether infants' saccades following the probe are consistent with an encoding of the stimulus sequence in terms of a series of retinocentric responses or in terms of the target's actual location on the presentation screen. Because determining saccade direction and endpoint from videotape can be difficult, we used an automated eye-tracking system to collect eye position data.

1. Experiment 1

1.1. Method

1.1.1. Participants

Eleven full-term 4-month-old infants (mean age = 122 days, S.D. = 6.4; four males) served as study participants. The majority of the infants were recruited for the study by advertisements placed in newspapers and magazines and from flyers placed in strategic locations around London. An additional six infants were tested but eliminated from the analysis due to fussiness ($n = 1$), failure to calibrate the eye-tracker ($n = 2$), or failure to meet trial or anticipatory look criteria ($n = 3$). All participants were healthy and free from any known neurological or ocular abnormality.

1.1.2. Apparatus

The testing room was dimly lit. Infants sat in a car seat on a wooden platform 70 cm distant from an infrared camera and 90 cm distant from a monitor screen. Attached to the seat was a padded head-guard that helped to keep the infants' heads facing straight ahead. Participants' eye movements were measured using an Applied Science Laboratory Model 504, 50 Hz corneal reflection eye tracking system that is accurate to 1° of visual angle following a two-point calibration procedure. This system uses a remote pan/tilt infrared camera, which was centrally positioned on a table in front of the stimulus display monitor. The system was setup with a 25 cm achromatic monitor for viewing the infant's eye during the experiment. A larger monitor and video mixer were setup to provide a mixture of three superimposed images: the infants face, the experimental stimuli, and cross hairs representing the location of the infant's gaze. The image on this monitor was recorded onto videocassette for coding following the experiment. The parent typically stood behind the infant so that she did not disrupt the experiment. A colour monitor was used to present the stimuli to the infants. Black felt was placed around the border of the monitor and a 2 m tall black screen stood to the side of the monitor blocking the infants view from the remainder of the room.

1.1.3. Procedure

1.1.3.1. Eye-tracker setup and calibration. After the infant was placed in the seat, the room lights were dimmed and a short video was shown on the monitor. The purpose of this video was to attract the infant's attention towards the monitor so that we could locate the infant's eye with the eye-tracker's infrared camera. Two experimenters were necessary to calibrate the eye-tracker and run the experiment. Experimenter 1 controlled the infrared camera using a remote control. Although the camera was usually in automatic mode (i.e., it follows the participants eye-gaze using algorithms included with the eye-tracker), it was necessary before starting the experiment to "find" the infant's eye using the remote. Once the eye was found, the automatic system was turned on. Occasionally, if the infant moved his head quickly during the experiment, the automatic system lost track of the eye. In this situation, Experimenter 1 would again find the eye using the remote control while viewing the infant's pupil on the 25 cm achromatic monitor. Experimenter 2 controlled computer running the software associated with the eye-tracker. Infrared illumination, pupil and corneal reflection settings, and automatic and manual tracking modes were adjusted by Experimenter 2 during the movie and the experiment so that a good image of the eye were visible on the small monitor and trackable by the eye-tracker.

To calibrate the system, the movie that the infants had been watching vanished and a different movie appeared on the left top corner of the monitor. This movie subtended a visual angle of approximately 1.9° . When Experimenter 2 noticed that the infant had directed her gaze to that part of the screen, he instructed the computer to store that point. This was repeated for another point at the bottom right of the display monitor's screen. The movie was then presented in five random locations on the screen and Experimenter 2 watched the cross-hairs on the main experimental monitor to determine if the eye-tracker was tracking the infant's gaze. If not, the calibration was repeated until it worked correctly.

1.1.3.2. Stimuli. All stimuli were created and presented with MATLAB using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) on a Macintosh G4 computer. Sixteen different pictures were used as the target stimuli and a black dot was used as the "drift" stimulus. The pictures were various colourful cartoon-like pictures based primarily on clip-art freely available on the Internet. All pictures were modified to be squares of exactly the same size measuring approximately 8° at the specified viewing distance. A schematic of the stimulus presentation sequence is illustrated in Fig. 2.

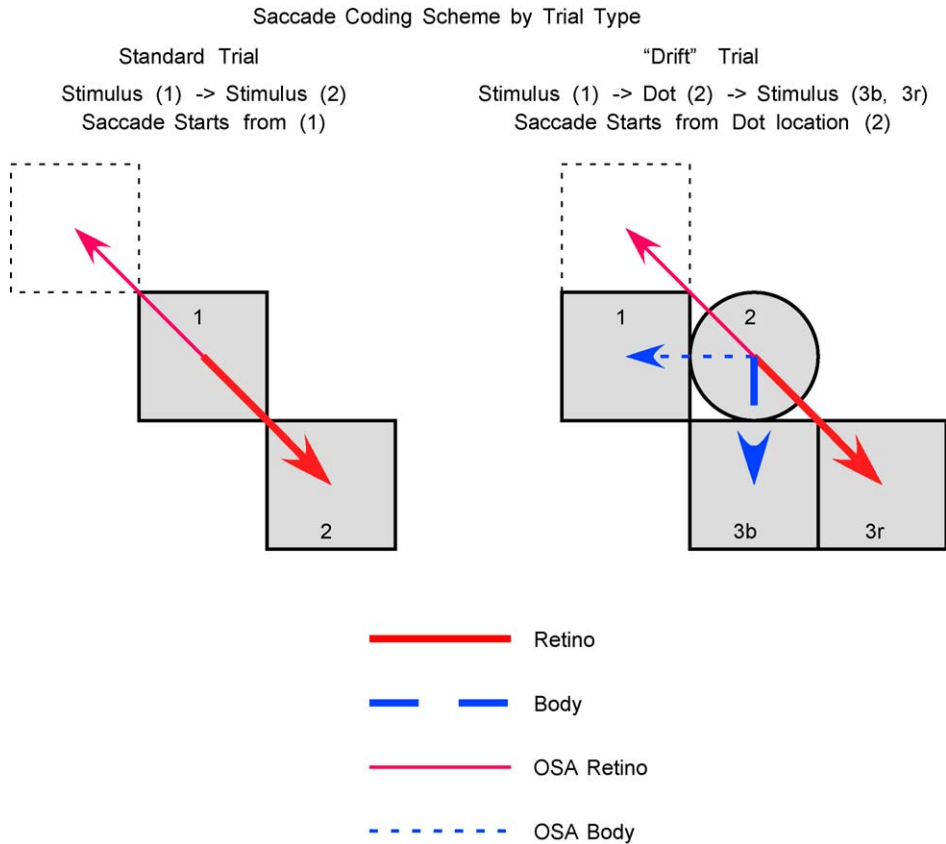


Fig. 2. Design of Experiments 1 and 2. Standard sequence: Items appeared in alternating locations for 700 ms separated by a 700 ms ISI. Drift sequence: The first 200 ms of the ISI was replaced with the appearance of a black dot in order to cause attention to “drift” away from the standard stimuli positions. After the disappearance of the black dot and the ISI, two pictures appeared simultaneously. One picture appeared in the same location that it would appear in during the standard sequence. The other picture subtended the location that would be specified by a retinocentrically oriented saccade originating from the black dot.

In the standard trial type, pictures were presented in two alternating locations on the screen. The centre of the first location was 4.4° from the screen’s centre at an angle of 45° above and to the left of the centre. The second location was at an angle of 45° below and to the right of centre. Each stimulus was presented for 700 ms, with a 700 ms interstimulus interval (ISI) during which the screen was blank. Trials were presented continuously (without gaps) and alternated from a beginning point at the top-left or the bottom-right positions. Two out of every 11 stimulus presentations involved a “drift” trial, in which a black oval (“dot”) was presented for the first 200 ms of the inter-stimulus interval (ISI). The dot appeared in one of two locations depending on the position of the current stimulus. One location was 4.4° to the right of the upper left standard stimulus. The other was the same distance to the left of the bottom right standard stimulus. The dot appeared always at the same vertical level of the currently presented standard stimulus. Thus, it was either to the right of the higher standard stimulus or to the left of the lower standard stimulus. Five hundred milliseconds following offset of the dot, the next standard stimulus appeared. Drift presentations were separated by at least three standard presentations, but were otherwise presented at random intervals. Each infant watched the sequences for a minimum of 55 stimulus presentations.

1.1.3.3. Data scoring, coding, and reduction. One coder blind to the purposes and hypotheses behind the experiment coded the videotapes of each participant’s eye-tracker data. The coder determined the place, direction, and timing of each saccade for each trial. Locations for saccade start and end points were collapsed to a 4×4 grid (see Fig. 3). Another experimenter coded the directional information from a subset of infants in order to compute reliability ($n = 6$, Cohen’s kappa = 0.90).

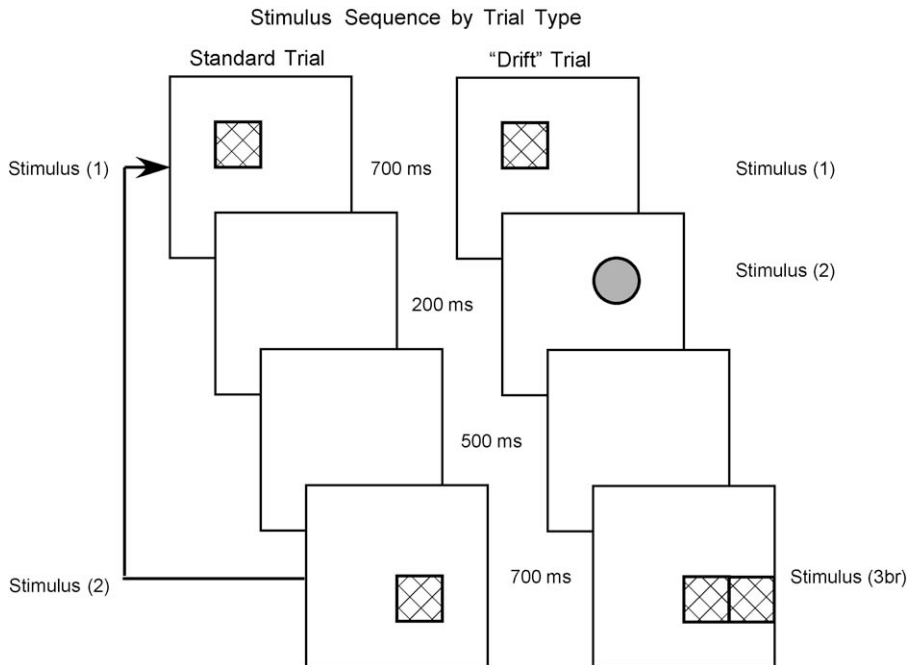


Fig. 3. Saccade coding scheme. The arrows represent the typical saccade directions from the black dot. OSA-body and OSA-retino refer to the directions that would have been expected based on body- or retino-centred responses if infants were inadvertently advanced one step ahead in the sequence.

We focused on the ratio of anticipatory to reactive saccades as well as the reaction times of reactive saccades as a function of condition. Therefore, trials were only retained when infants were fixating the stimuli. Furthermore, because we were interested in the direction of saccades relative to the saccade starting point, it was imperative that the saccades begin at particular locations. We thus eliminated from analysis all saccades that did not previously originate from a location containing a stimulus presentation. Additionally, we eliminated from analyses saccades in the trial following a drift trial, since these represent responses following an interruption of the ongoing alternating pattern. Furthermore, a preliminary analysis determined that infants typically made eye movements that were chaotic following the disappearance of the two simultaneously presented pictures shown during the drift trials. The mean number of trials retained after data reduction for each infant was 48 (S.D. = 30) out of an initial mean of 108 (S.D. = 54) stimulus presentations.

From these data, we selected those infants who met two criteria: each participant had watched at least six drift sequences and had made at least four anticipatory saccades during these sequences. The average number of drift trials per infant scored using these criteria was 6.0 (S.D. = 3.4). In order for a saccade to be labelled 'anticipatory' we kept to criteria used by [Wentworth, Haith, and Hood \(2002\)](#):

- Criterion 1: A saccade had to have been made less than 200 ms after the onset of the target picture.
- Criterion 2: A saccade had to have been made to a point on the screen relatively close (within 1.9° of visual angle) to an edge of target picture.
- Criterion 3: The infant's gaze had to remain in this location until the target's appearance (this criterion was obviously not relevant for anticipations that followed the appearance of the target). An anticipation rate for each participant was calculated using the formula:

$$\frac{\text{anticipations}}{\text{Anticipations} + \text{reactions}}$$

Reactions began at the previous target location and arrived at the current target location more than 200 ms after the current targets appearance. Reaction latencies were calculated for each codable and directionally correct non-anticipatory saccade.

Analyses were carried out on anticipatory saccades following a saccade to the “dot” stimulus during the drift sequence presentations. Pilot results showed that infants made over 90% of such saccades in one of four directions. These directions (illustrated in Fig. 3) were categorised as “retino-specified” (Retino), “body-specified” (Body), “one-step-ahead-retino” (OSA Retino), and “one-step-ahead-body” (OSA Body). The retino-specified direction is the direction that would be expected if infants had not taken into account their prior lateral saccade to the dot when making an anticipatory saccade to the next stimulus. Body-specified refers to a movement that does take into account the saccade to the dot and leads the infant to look at the actual screen location of the next stimulus presentation. One-step-ahead-retino refers to retinocentric saccade that would be expected had the infant encoded the dot as another part of the repeating sequence. That is, it would be the retinocentric response expected from the other stimulus in the standard sequence. One-step-ahead-body refers to a saccade that would be expected if infants were advanced one step ahead in the sequence and looking for the other stimulus in the standard sequence. Note that this latter type of response represents a return of gaze from dot to the place where the infant had been looking prior to the dot’s appearance. While OSA responses were common following drift presentations (see Section 1.2), an analysis of a subset of the data from six participants determined that these responses were extremely uncommon following standard trial presentations (5 OSA responses after 331 presentations). Therefore, we coded for these responses only for drift trials.

1.2. Results

1.2.1. Standard trial anticipations

Our first analysis focused on the standard alternating sequence in which no drift stimulus appeared. The overall anticipation rate was 38% (S.D.=0.11). The number of anticipatory saccades to the top-left position and the bottom-right position of targets were also calculated and compared using a paired-samples *t* test. The test did not indicate a significant difference, $t(10)=0.23$. Consequently all subsequent analyses of normal sequence saccades were performed without respect to picture location. In order to explore the time-course of learning we correlated trial number with the percent anticipations achieved to that point in the sequence. This revealed a nonsignificant ($r=0.03$) correlation. Because different subjects experienced varying numbers of trials, we also correlated the binary measure of anticipation with the percent of trials completed. This also resulted in a nonsignificant correlation ($r=0.04$). Fig. 4 plots the average proportion of anticipations as a function of stimulus exposure. These results suggest that infants picked up on the sequence after only a short number of presentations. Regarding reaction responses, the group mean of mean latency saccades to both top-right and bottom-left targets was 320 ms (S.D. = 84.2).

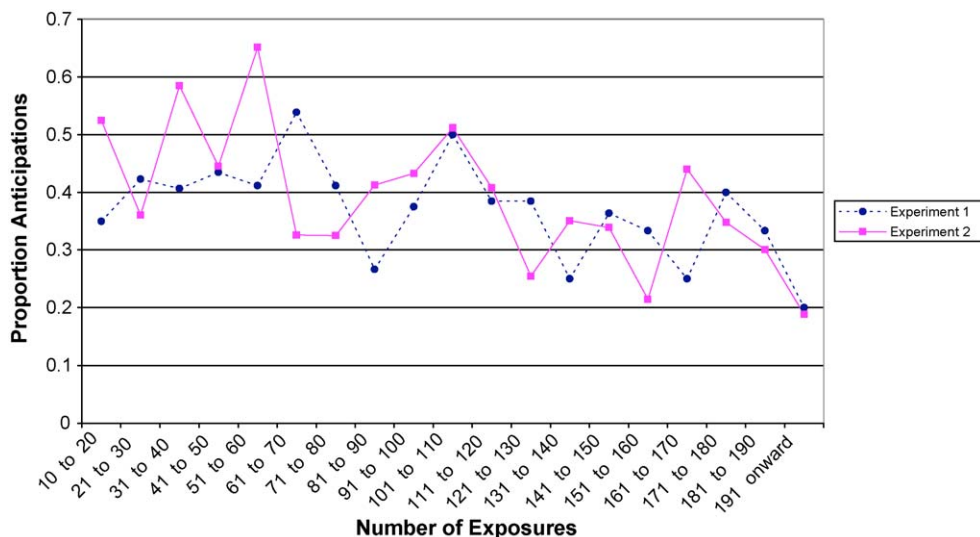


Fig. 4. Proportion of anticipations across 10 trial bins in Experiment 1.

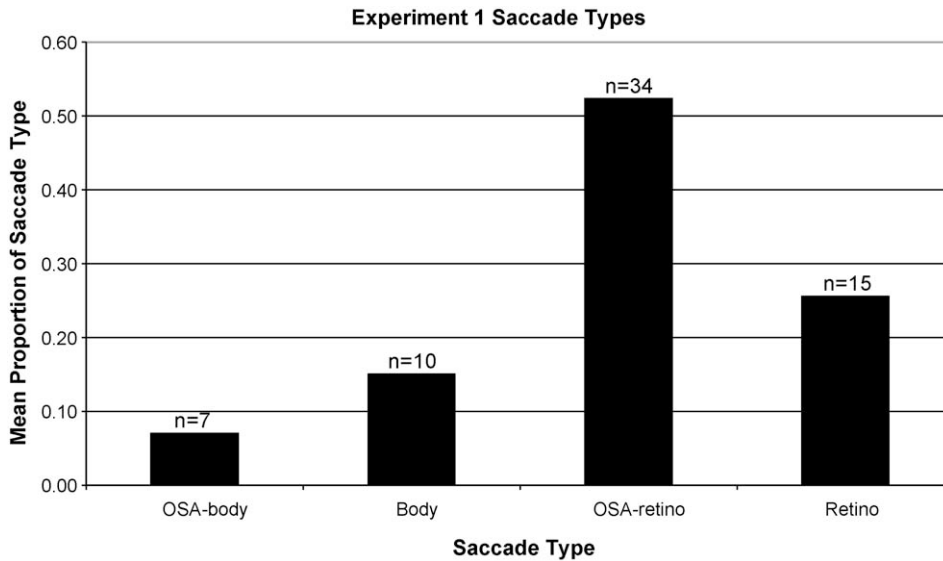


Fig. 5. Distribution of scorable saccades on drift trials in Experiment 1.

1.3. Drift trial anticipations

The average rate of anticipatory looking on drift trials (in any of the four directions described above) for all subjects was 57% (S.D. = 0.26). A paired *t*-test analysis confirmed that the rate of anticipation on drift trials was significantly higher for drift trials than for trials in the normal alternating sequence ($t = -3.2, p < 0.01$). This enhanced anticipation rate probably resulted from our discounting any drift trials in which infants did not fixate the dot—thus we required a greater level of attention on the drift trials than trials in the standard sequence. A Friedman two-way analysis of variance was used to analyze the types of anticipatory saccades that infants made in drift. This involved assigning a series of ranks from one to four for each infant based on the number of saccades that fell into the four categories described previously. The analysis revealed that certain types of saccades were made more frequently than others, χ^2 (d.f. = 3, $N = 11$) = 11.2, $p < 0.05$. This finding was further analyzed with Wilcoxon matched-pairs test indicating that only OSA-retinocentric responses occurred at a rate significantly higher than would be predicted by chance ($z = 2.72, p < 0.01$). Comparisons of chance responding with body-centred ($z = -1.075, p = 0.28$) and retino-centred ($z = -0.357, p = 0.72$) responses did not reveal significant differences. One-step-ahead body responses occurred at a rate significantly lower than chance ($z = -2.77, p < 0.01$). The distribution of the saccadic responses is illustrated in Fig. 5.

1.4. Reactive saccades

All reactive saccades were made to actual locations of stimuli during the normal sequence and drift trials (i.e., there were no reactive saccades to one-step-ahead locations because there were no actual stimuli in these locations—thus there was nothing to react to). Mean reaction times to stimuli were computed for each infant for normal sequence saccades and to each of the two drift stimulus locations. These scores were evaluated using one-way repeated measures ANOVA that determined that there was no main effect of saccade type on reactive saccade latency, $F(3,20) = 0.66$.

1.5. Discussion

When presented with a sequence of visual events that appeared in largely predictable spatial positions with predictable temporal properties, 4-month-olds appeared to encode the retinocentric locations of the target positions more reliably than the actual position of the targets relative to the screen or to their bodies. These results provide converging evidence for the view offered in Gilmore and Johnson (1997a) that retinocentric representations predominate saccade planning in infants younger than 6–7 months at least under some circumstances. Because the targets here, unlike those

in the Gilmore and Johnson studies, were presented in positions held constant relative to the background screen, this result casts doubt on the alternative interpretation that infants were not responding retinocentrically, but representing each object's location relative to the screen. Moreover, the results show that the previous findings from the double-step saccade paradigm extend to circumstances when infants are not merely reacting to the appearance of visual stimuli, but are actually forming expectations about their spatial and temporal properties.

An unexpected finding of interest is that not only did the intermediary black dot succeed at leading infants' saccades to drift away from the learned sequence on some occasions, but it also seemed to advance infants one step temporally in the sequence on others. That is, while most responses were retinocentric, a significant number were consistent with a retinocentric response that would have been expected had infants been one step ahead in the sequence.

This suggests that infants may have confused the black dot for part of the actual repeating sequence despite the fact that it was in a new position and lacked the vibrant surface colours and visual complexity indicative of the repeating stimuli. One problem with this interpretation is that it leaves open the possibility that infants' responses were not actually performed with a retinocentric frame of reference but with an object-centred frame. That is, infants may have learned to look in a position on the screen relative to the last stimulus in the sequence rather than having only learned to make a saccade in a certain direction. Little is known about the early development of object-centred representations, but what evidence exists suggests that they can influence saccade planning in infants as young as 8 months of age under some circumstances (Johnson & Gilmore, 1998).

In order to evaluate the possibility that object-centred representations guided infants' responses in the VExP, we performed Experiment 2 in an attempt to better disambiguate the dot from the normal alternating sequence. We hypothesised that a dot that was more obviously different from the normal stimuli would be less likely to be perceived as part of the sequence. Thus, if infants had been acting upon an object-centred frame of reference (rather than a retinocentric one), they should instead make most of their subsequent responses towards the target's actual standard sequence location on the screen. However, if infants in Experiment 1 had been acting upon a retinocentric frame of reference, they should continue to do so in Experiment 2. The only difference in behaviour we would expect in this case is that the dot should no longer advance them one step in the alternating sequence.

2. Experiment 2

In order to make the black dot seem less part of the sequence, we changed the sequence so that it did not change with each presentation as it did in Experiment 1. In Experiment 2, the picture shown to the infants remained the same (regardless of its location) until the infant looked away from the stimulus completely. When a lookaway did occur, a new picture was shown to reengage infants' interest. Although, the black dot was identical to that used in Experiment 1, we hypothesised that it would stand out more as distinct from the sequence because the sequence itself did not vary. The second reason for making this change was based on results by Adler and Haith (2003) that showed that a greater number of anticipatory saccades are made when the stimuli are invariant than when they vary across presentations.

2.1. Method

The methods for Experiment 2 differed from Experiment 1 in that the stimuli on the monitor did not change with each presentation. Instead, the same stimulus picture was presented (in both of the standard locations) until infants turned away from the monitor. After a look away, an experimenter key-press instructed the computer program to change the stimulus picture (to re-engage the infant's interest). In all other respects Experiment 2 was run in the same way as Experiment 1. Twelve infants (mean age = 120 days, S.D. = 7.6; five males) met all criteria for inclusion in the experiment and their data was analyzed. One additional infant was tested but was not included due to fussiness.

2.2. Results

2.2.1. Standard trial sequence

Infants saw an average of 112 (S.D. = 45) standard trials towards which they made an average of 44 (S.D. = 11) anticipatory saccades. The overall anticipation rate for Experiment 2 was 43%. A comparison to the 39% anticipation rate of Experiment 1 did not reach statistical significance, $t(22) = 1.20$. As in Experiment 1, we correlated trial number with the percent anticipations achieved to that point in the sequence, which revealed a nonsignificant ($r = 0.06$) corre-

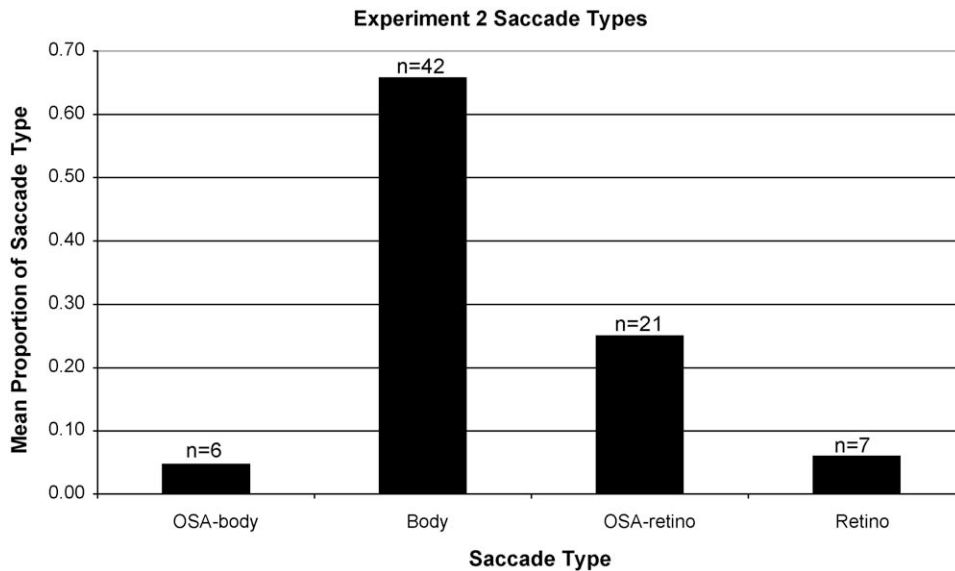


Fig. 6. Distribution of scorable saccades on drift trials in Experiment 2.

lation. There was also no significant ($r=0.07$) correlation between percent anticipations achieved and the percent of trials completed. Percent anticipations are plotted as a function of trial exposure in Fig. 4. The mean latency (over the entire sample of all participants' reactive responses) was 320 ms (S.D. = 79.6).

2.2.2. Drift trial sequences

The average number of drift trials was 6.9 per infant (S.D. = 2.9). The average rate of anticipations on drift trials for all subjects was 56% (S.D. = 0.20). A paired t -test analysis confirmed that the rate of anticipation on drift trials was significantly higher for drift trials than for trials in the normal alternating sequence, $t(11) = 2.5$, $p < 0.05$.

The Friedman two-way analysis of variance on the ranks of saccade numbers to the four target locations revealed that the saccade types were not equally distributed, χ^2 (d.f. = 3, $N = 11$) = 18.1, $p < 0.0005$. This finding was further analyzed with Wilcoxon matched-pairs test indicating only body-centred responses occurred at a rate significantly higher than would be predicted by chance ($z = 2.71$, $p < 0.01$). OSA-body responding ($z = -2.94$, $p < 0.005$) and retinocentric responding ($z = -3.0$, $p < 0.005$) were significantly less frequent than chance. A comparison of chance responding with 'OSA-retinocentric responses ($z = -0.045$, $p = 0.96$) did not reveal a significant difference. The distribution of the saccadic responses is illustrated in Fig. 6.

3. General discussion

The results of the two experiments considered together bring to light a number of important findings about infants' spatial frames of reference for anticipatory action. When a target sequence had largely predictable spatial and temporal properties, but unpredictable visual forms, 4-month-old infants made more saccades based on retinocentric information about the target positions than other sources. In contrast, when the spatial, temporal and visual form of the targets was consistent, infants made significantly more body-centred responses than retinocentric ones. These results have several implications. Consistent with Kaufman and Needham (1999), it appears that a number of frames of reference, including body-centred ones, may be available for saccade planning to infants between 4- and 6-months of age depending on the context. Further, the observation that 4-month-olds consistently used retinocentric information in planning saccades in Experiment 1 supports the argument made by Gilmore and Johnson (1997a, 1997b) that retinocentric representations emerge early, and that the use of higher order frames occurs over an extended developmental period.

At the same time, these data show that the double-step saccade task may have underestimated the capacity of young infants to use body-centred information about target positions. Comparisons between Experiments 1 and 2

demonstrate that the conditions in which infants show and/or use certain frames of reference is strongly influenced by the task in which they are engaged. Specifically, the degree of consistency in the visual targets appears crucial. While we cannot be certain why keeping the visual stimuli consistent within an experiment lead infants to demonstrate utilise body-specified frame of reference more frequently, we suggest two possibilities that could be examined with further research.

The first possibility is that when the stimuli change from presentation to presentation, infants focus greater attentional resources on the changing visual characteristics of the stimuli than they do when the stimuli remain relatively constant. In other words, the use of varying targets in Experiment 1 made the task more complex and therefore more resource-demanding than that of Experiment 2. In formal terms, computing body-centred position from retinal position requires the systematic integration of eye, head, and possibly trunk position, whereas retinocentric position may be derived directly from the topographic projection from the retina. This suggests that infants' performance in the two paradigms was subject to a capacity constraint that led, in the more complex scenario of Experiment 1, to more saccades based on the simpler, less resource-demanding representation provided by retinal position. Some evidence for this possibility has been provided by Richardson and Kirkham (2004) who found that 6-month-old infants in a multi-modal learning task had their spatial learning disrupted when the featural identity of the stimuli was varied.

It should be noted that this argument about capacity constraints leading infants to adopt simpler spatial representations cannot easily distinguish which non-retinal frame was in competition with the retinocentric position encoding. As discussed earlier, prior work by Kaufman and Needham (1999) suggested that allocentric frames of reference might be available to infants by 6 months. Thus, it is possible that both body- and environment-centred spatial representations develop rapidly between 4 and 6 months. On the other hand, Bremner (1978a, 1978b) has shown that allocentric frames of reference are available to infants at about 8 months of age, but only when there are direct and salient landmarks available. The infants in the current set of VExP studies were considerably younger than those tested by Bremner and the dimmed room provided little that could be considered a salient landmark. There was nothing available on or around the monitor that could be considered a valuable landmark. Furthermore, Kaufman and Needham (1999), who found allocentric coding in the absence of salient landmarks, measured overall levels of interest, which may not directly relate to spatial frames for saccadic action studied here.

A second possibility is that infants were using an object-centred frame of reference in both Experiments 1 and 2. By object-centred, we refer to a frame of reference in which spatial locations are coded with respect to a particular object or stimulus' position. Unlike actions based on a retinocentric frame, intermediary eye movements should not affect actions based on an object-centred frame. In Experiment 1, if the dot were seen as a normal part of the sequence, an object-centred frame of reference would lead the infants to make a saccade based on the location of the dot. In contrast, In Experiment 2, the black dot may not have been perceived as part of the alternating sequence of stimuli, thus infants made a saccade based on two sources of information: the location specified by the position of the last item in the sequence; their current eye position. In this way, an object-centred frame of reference can be thought of as more "advanced" than a retinocentric frame of reference because it allows infants to compensate for current eye position. There are some interesting parallels between this work and work on the development of other spatial frames of reference. For example, Hermer and Spelke (1994, 1996) proposed that toddlers are incapable of using non-geometric cues to reorient themselves following disorientation. However, just as stable featural cues lead infants to use a body-centred reference in the experiments described here, Newcombe and Huttenlocher (2000) found that when stable and salient landmarks (such as a door) were available to the toddlers, they reoriented using these landmarks. The present study combined with the findings of Kaufman and Needham (1999) and Newcombe and Huttenlocher (2000) suggest that while development clearly occurs in children's use of different spatial frames, humans at any age are not limited to a particular frame of reference.

In summary, the results of the studies reported here help to complete what has been a somewhat fragmented account of the development of spatial frames of reference. Consistent with the earlier findings of Gilmore and Johnson (1997a, 1997b), 4-month-old infants appear to use the retinal position of visual targets in planning not just responsive saccade sequences, but anticipatory saccades to predictable targets when the task places high demands on the infants' attentional and cognitive resources. On the other hand, when given relatively invariant stimuli that likely reduce cognitive load, young infants successfully encode the object-centred position of visual targets. Taken together, the results suggest that the primitive retinocentric representation of visual location influences young infants' saccades in only limited or unusual circumstances (cf. Brown et al., 2003), and that more flexible and powerful spatial representations are provisionally available from the first several months after birth.

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