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Developmental Changes in How Head Orientation Structures Infants' Visual Attention

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ABSTRACT

Most studies of developing visual attention are conducted using screen-based tasks in which infants move their eyes to select where to look. However, real-world visual exploration entails active movements of both eyes and head to bring relevant areas in view. Thus, relatively little is known about how infants coordinate their eyes and heads to structure their visual experiences. Infants were tested every 3 months from 9 to 24 months while they played with their caregiver and three toys while sitting in a highchair at a table. Infants wore a head-mounted eye tracker that measured eye movement toward each of the visual targets (caregiver's face and toys) and how targets were oriented within the head-centered field of view (FOV). With age, infants increasingly aligned novel toys in the center of their head-centered FOV at the expense of their caregiver's face. Both faces and toys were better centered in view during longer looking events, suggesting that infants of all ages aligned their eyes and head to sustain attention. The bias in infants' head-centered FOV could not be accounted for by manual action: Held toys were more poorly centered compared with non-held toys. We discuss developmental factors—attentional, motoric, cognitive, and social—that may explain why infants increasingly adopted biased viewpoints with age.

Screen-based tasks, in which infants look at stimuli on a computer display, are the primary means of studying the development of visual attention (Oakes and Amso 2018). Although screen-based tasks afford excellent experimental control, they suffer from several important limitations (Franchak and Yu 2022). First, visual stimuli that experimenters typically choose to display are unlike the rich, complex visual scenes that infants experience in everyday life (Franchak 2020b). Second, passively viewing stimuli is not how visual attention functions in everyday life—visual attention is actively deployed to support ongoing action and social interactions (Foulsham, Walker, and Kingstone 2011; Franchak, Kretch, and Adolph 2018; Land 2006; Yu et al. 2009). Third, observers move only their eyes to scan the contents of a screen, but in real life, movements of both the eyes and head work in concert to allow observers to select what is in view from moment to moment (Einhauser et al. 2007; Franchak, McGee, and Blanch 2021; Land 2004).

Here, we consider the impact of this third limitation on our knowledge of visual attention development. Specifically, to what extent do embodied factors—infants' bodies and motor abilities—contribute to infants' visual attention? Prior work examining two embodied factors, body size and posture, indicates that the motor system shapes and constrains what infants see. Infants' short arms make held objects appear large in the visual field (Suanda, Smith, and Yu 2017; Yu and Smith 2012; Yu et al. 2009). Body posture influences visual experiences by altering the location and orientation of the head (Frank et al. 2013; Kretch, Franchak, and

Adolph 2014; Luo and Franchak 2020). For example, crawling infants are more likely to look at targets on the ground, whereas walking infants are more likely to look at elevated targets, such as caregivers' faces (Franchak, Kretch, and Adolph 2018; Kretch, Franchak, and Adolph 2014). However, demonstrating that infants' perception is *influenced* by the motor system does not address how infants learn to *coordinate* the motor aspects of looking to distribute visual attention to targets of interest. Understanding how infants use their eyes and heads relative to external visual targets will add to our theoretical understanding of the embodied aspects of visual attention and how they develop.

For adults, aligning the eyes and head to look at a target facilitates visual, motor, and cognitive processes (Biguer, Prablanc, and Jeannerod 1984; Nakashima and Shiori 2014; Thaler and Todd 2009). For example, visual search reaction time suffers for foveally presented visual targets when the eyes and head are misaligned (Nakashima and Shiori 2014). Moreover, when completing a cognitive task with peripherally presented visual information, participants are more likely to move their heads to center information when the task is difficult (Dunham 1997). But looking with aligned eyes and head is not automatic. Tightly coordinated movements of the eyes, head, and body are required to allow gaze to be shifted from one location to another (Franchak, McGee, and Blanch 2021; Gibson 1979; Land 2004; Pelz, Hayhoe, and Loeber 2001; Solman, Foulsham, and Kingstone 2017). If a to-be-attended object is out of view or far away from the foveal center, the head is used to make large shifts of the field of view (FOV), whereas the eyes make more fine-grained selections within the FOV (Stahl 2001) and keep gaze stabilized on targets by compensating for head movements (Land 2006).

The current study tested infants' (9–24 months) developing ability to align their eyes and head to center gaze targets in view. We attempted to distinguish between two alternative hypotheses. One hypothesis is that infants orient relevant information in their head-centered FOV, facilitating looking with aligned eyes and head. Alternatively, eyes and head may be decoupled, with infants failing to adopt efficient, adultlike head alignment to task-relevant targets. Because past work only tested how infants' visual attention is constrained by head and body position in *different postures* (Franchak, Kretch, and Adolph 2018; Kretch, Franchak, and Adolph 2014; Luo and Franchak 2020), it is unknown how infant visual attention is related to the head-centered view *within a posture*. Moreover, if infants do coordinate eyes and head to center targets in view, how does such centering develop over the first 2 years?

Several related lines of evidence lead us to predict that infants center information in the head-centered view rather than look with decoupled eyes and head. First, infants achieve an adultlike ability to move their eyes and heads together by 28 weeks of age, suggesting that infants possess the motor skills needed to align the eyes and head toward relevant information (Daniel and Lee 1990; Regal, Ashmead, and Salapatek 1983). Orienting the eyes and head depends on postural support from the trunk. By 6–8 months, infants who can sit independently adjust their postural sway while sitting to facilitate visual attention to external visual targets (Pham et al. 2024) and to objects held in their own hands (Arnold et al. 2020). By 12 months, they suppress head movements when gaze is directed toward an object, helping to stabilize visual attention (Borjon et al. 2021). However, changes between 12 and 36 months in how eye and head movements are recruited to shift gaze to peripheral targets suggest that some refinement may occur in task-specific attention control (Nakagawa and Sukigara 2013).

Second, naturalistic studies of looking behavior find that the eyes are most often centered within the head in infants (Bambach, Crandall, and Yu 2013; Bambach et al. 2014, 2016; Borjon et al. 2021; Kretch and Adolph 2015) as they are in adults (Einhauser et al. 2007; Foulsham, Walker, and Kingstone 2011), suggesting that infants move the head to center targets of interest in view. Indeed, Borjon et al. (2021) found no difference in the position of the eyes within the head from 12 to 24 months.

Third, infants vary head movements according to different sub-activities during social interaction, which may serve to bias their view toward particular types of information (Schillingman et al. 2015). A *biased viewpoint* may facilitate visual attention in real-world settings: In a cluttered environment with multiple targets in different spatial locations, centering one target means that targets in other locations will be poorly centered in view. Adults select eye and head movements to deal with trade-offs based on task constraints: They bias task-relevant information at the expense of task-irrelevant information (Einhauser et al. 2007; Land 2004; Pelz, Hayhoe, and Loeber 2001; Smeets, Hayhoe, and Ballard 1996; von Laßberg et al. 2014). Do infants?

Face-to-face play with infants and caregivers seated across from each other creates competition among potential gaze targets. From infants' perspective, caregivers' faces will be higher in infants' visual fields, whereas toys resting on a table or held by either partner will be lower in the visual field. Even though infants coordinate eyes and head in some situations (Borjon et al. 2021; Regal, Ashmead, and Salapatek 1983), it may not be possible for infants to do so equally well for targets in different physical locations, such as toys and faces. For example, infants' ability to center toys in view depends on their body posture—while prone, infants struggle to center distant objects in view but can better align their eyes and heads to look at objects from a sitting or upright position (Luo and Franchak 2020). While sitting, infants more actively stabilize body posture to look at a toy held by another person compared to one held in their own hands (Arnold et al. 2020). Thus, looking with aligned eyes and head is not constant from moment-to-moment but may depend on the relative location of targets in infants' view. How might infants cope with competition between toys and faces? Like adults, they may bias their view toward more task-relevant information. In play with objects and caregivers, infants tend to spend more time looking at toys rather than faces (de Barbaro et al. 2015; Franchak, Kretch, and Adolph 2018; Yu and Smith 2013). Here, we ask whether this asymmetry might extend to how infants align eyes and head to center toys versus faces in view.

1 | Current Study

We studied how infants' head-centered FOV relates to visual attention in the context of infant–caregiver play with toys. The rationale for the task was threefold. First, this type of play creates situation where visual attention must be divided from moment to moment between targets in different spatial locations (toys and faces), and prior work suggests that infants will preferentially attend to toys (de Barbaro et al. 2015; Franchak, Kretch, and Adolph 2018; Yu and Smith 2013). Crucially, this allows us to test whether infants align eyes and head to look at toys *at the expense* of centering faces in view. Second, playing while sitting in a highchair was desirable to isolate the head-centered FOV within a supported sitting posture without interference from shifting among different postures (and thus different viewpoints). Third, it is an everyday learning context wherein infants play with toys and with their parents, and wherein they learn about visual objects and object names: By 12 months of age, sitting is the most common body position that infants experience in daily life (Franchak 2019; Franchak, Kadooka, and Fausey 2024). Although we cannot claim that results from this situation will generalize to other everyday situations (such as when infants and caregivers move freely), this study provides an important first step in addressing how eyes and head are coordinated in one common context.

Infants wore a head-mounted eye tracker (Figure 1A) that measured eye movement position and recorded videos of infants' head-centered FOV (Franchak et al. 2011). We detected the locations of toys and faces within the FOV video to determine how infants centered different types of targets when looking at each target (Figure 1B). *Centering* of toys and objects in the FOV camera image (distance from the center of the FOV) served as a measure of orienting: Targets were poorly centered when located on the edges of the FOV image (large distance to center) but were well centered when located in the middle of the FOV image (small distance to center).

Our overall hypothesis is that when faces and toys compete for infants' attention, *infants will bias their viewpoint to center the most task-relevant information in view, and this bias should increase with age*. Because infants spend more time looking at toys rather than faces in the age range tested (Franchak, Kretch, and Adolph 2018; Yu and Smith 2013), we predicted that infants would be biased to center toys in view as opposed to faces. This bias may occur as a consequence of infants increasingly pointing their heads down to center toys in view, putting faces farther from the center of view. We studied infants from 9- to 24-month-olds (every 3 months) because 9 months has been identified as the age at which the shift to increased object attention (over faces) begins (de Barbaro et al. 2015) and predicted that infants would adopt an increasingly biased view with age.

We tested additional hypotheses regarding visual-motor behaviors that might moderate the degree to which gaze targets are centered in view. First, *if centering supports attention, centering should be better during longer looking episodes*. Longer looking episodes are indicative of moments when infants show interest in and/or increased cognitive processing of a particular target. Because infants suppress head movements during looks to objects (Borjon et al. 2021), stabilized gaze may help maintain better eye-head alignment during longer looking episodes. It is also possible that infants may choose to look longer toward targets that are already centered in view. Thus, we predict that targets will be better centered during longer looking episodes compared with shorter looking episodes. Second, *if centering is a consequence of visual–manual control*, toys held in infants' hands may be better centered compared to non-held toys. Centering an object aligns

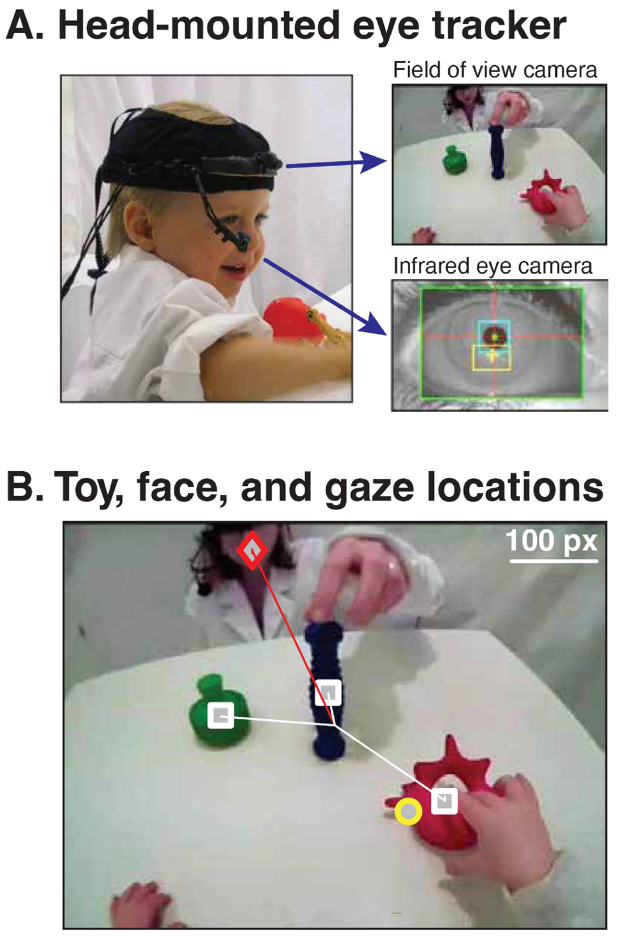

FIGURE 1 | (A) Infants wore a head-mounted eye tracker that simultaneously recorded video of infants' eyes and field of view (FOV). (B) Toy, face, and gaze locations were determined within the FOV video for each frame. Toys (white squares) were detected automatically, and the caregiver's face (red diamond) was manually coded. Eye-tracking calibration determined the gaze location (yellow circle) within the FOV. Centering for each target was calculated as the distance of the target to the center of the FOV (length of the solid red and white lines). Smaller distance to center indicates better centering of gaze targets in the head-centered field of view. In this example, the blue toy was the best centered visual target (shortest line).

eye and head frames of reference to facilitate visual–manual control toward a target (e.g., reaching, manipulating) (Bertenthal and von Hofsten 1998). Moreover, prior work shows that infants' manual action toward objects can influence their appearance in the infants' viewpoint (Suanda, Smith, and Yu 2017; Yu and Smith 2012; Yu et al. 2009) and their postural control (Arnold et al. 2020).

2 | Methods

2.1 | Participants

The participants were drawn from a longitudinal study of infant–caregiver play (Borjon et al. 2021; Yu, Suanda, and Smith 2018). Overall, 99 sessions of data from 41 unique infants (20 females and 21 males) were included for analysis across 6 test ages: 9 months (21 sessions), 12 months (16 sessions), 15 months

(13 sessions), 18 months (17 sessions), 21 months (17 sessions), and 24 months (15 sessions). Experimental sessions, defined as a single trial of useable data, were selected for analysis from the larger study on the basis of three criteria: (1) good eye-tracking accuracy (spatial error <3°), (2) uninterrupted eye-tracking data (i.e., infants did not move or take off the eye-tracking headgear ensuring that accuracy was constant through the trial), and (3) an accurately positioned FOV camera (see below). Because of the strict inclusion criteria, the 41 infants contributed a varying number of sessions (ranging from 1 to 5 sessions, M = 2.41 sessions).

The study was conducted in accordance with the ethical standards of the American Psychological Association. The study procedures were approved by the Institutional Review Board of Indiana University. Guardians provided informed consent at the start of the study.

2.2 | Apparatus

Infants wore a Positive Science head-mounted eye tracker that was attached to a hat. The eye-tracking headgear contains two cameras (Figure 1A). The eye camera uses dark pupil tracking to detect movements of the pupil, and the FOV camera faces outward and records the infant's head-centered FOV. The diagonal of the FOV of the scene camera was 100°; FOV videos were recorded at 640 × 480 pixels at 30 frames/s. The eye and FOV videos were synchronously captured using a Geovision capture card (Model 1480B) for later processing.

Infants and caregivers sat across from one another at a children's play table (61 cm × 91 cm × 64 cm). Infants sat supported in a highchair, and caregivers sat on the floor. Participants were presented with three toys to play with; toy sets varied across age groups. Toys were sufficiently small (~290 cm^3) and light enough to be held in infants' hands. Each of the three toys was painted a different color (red, green, and blue) to facilitate the automatic detection of the toys using a computer vision procedure, detailed below. Additionally, the room, table, chairs, and clothes worn by infants and caregivers were white so that toys could be reliably detected in infants' FOV videos.

2.3 | Procedure

The experimental sessions analyzed in the current study were part of a larger study on infant social attention and object play with caregivers. In each session, infants and caregivers completed four trials playing with toys. Caregivers were told that the goal of the study was to observe how infants explore the toys, and they were encouraged to interact naturally with the infants and toys. Because of the laborious manual coding involved in these analyses, only the first trial that met the eye-tracking data quality criteria was used from each session. On average, trials lasted M = 96.1 s (SD = 27.0).

An eye tracker calibration procedure was completed at the start of the session. The FOV camera position was adjusted to ensure a consistent viewing angle across participants. With the infant seated in the chair and holding the head level (without any vertical tilt of the head), the FOV camera was adjusted to simultaneously capture the caregivers' face and the surface of the table. As in past work that used locations of targets in a FOV camera as a dependent measure (Kretch, Franchak, and Adolph 2014; Luo and Franchak 2020), some inconsistencies in FOV camera angle are possible (likely no more than 5°–10°). Any such angular errors would be randomly distributed across age, adding noise but not systematically biasing analyses. Afterward, infants were encouraged to look at a matrix of targets on the table spanning their FOV. The calibration stimuli were shown again at the end of the session to ensure that accuracy did not change throughout the session.

2.4 | Data Coding and Analysis

We used eye movement *XY* coordinates and face/toy *XY* locations (both in pixels of the FOV video) to determine when faces and toys were looked at, and, if so, where the face/toy was located within the FOV. The distance between the face/toy and the center of the FOV at the moment of looking served as a measure of *centering*. The length of the line from the center of the FOV to the face/toy location served as a measure of centering (solid red and white lines in Figure 1B). Larger centering values indicated worse orienting when faces/toys were far from the center of infants' view. Small centering values indicate moments when toys were closely centered in view. Figure 2 shows heatmap illustrations of face and toy locations (collapsed across individual toys) aggregated across all the frames for each age group. Below, we describe how eye movements, looking events, and target locations were derived in support of measuring centering.

2.4.1 | Toy Locations

To test our hypothesis about whether infants use their heads to center toys in view, we determined toy locations using automatic detection of toy locations in infants' FOV. Toy locations were detected using a series of computer vision algorithms as in past work (Yu et al. 2009). Blobs of pixels matching each of the toy colors (red, blue, and green) were identified on each frame. The centroid of those pixels was used as the toy location (white squares in Figure 1B).

2.4.2 | Face Locations

To determine how infants oriented their FOV to center faces, face locations were coded within the FOV video. Prior work (Bambach et al. 2014) and pilot testing showed that automatic detection of faces using computer vision algorithms was not sufficiently accurate, so manual coding was conducted. A custom Matlab program was created to allow coders to draw a box around the caregiver's face on each video frame (code available at https://github.com/JohnFranchak/roi_coder). Coders were instructed to draw the box to contain all areas between the ears (horizontally) and between the forehead to the chin (vertically). The center point of the box was used as the location of the caregiver's face (red diamond in Figure 1B). Periods where the caregiver's face was not contained in the FOV were excluded from analyses.

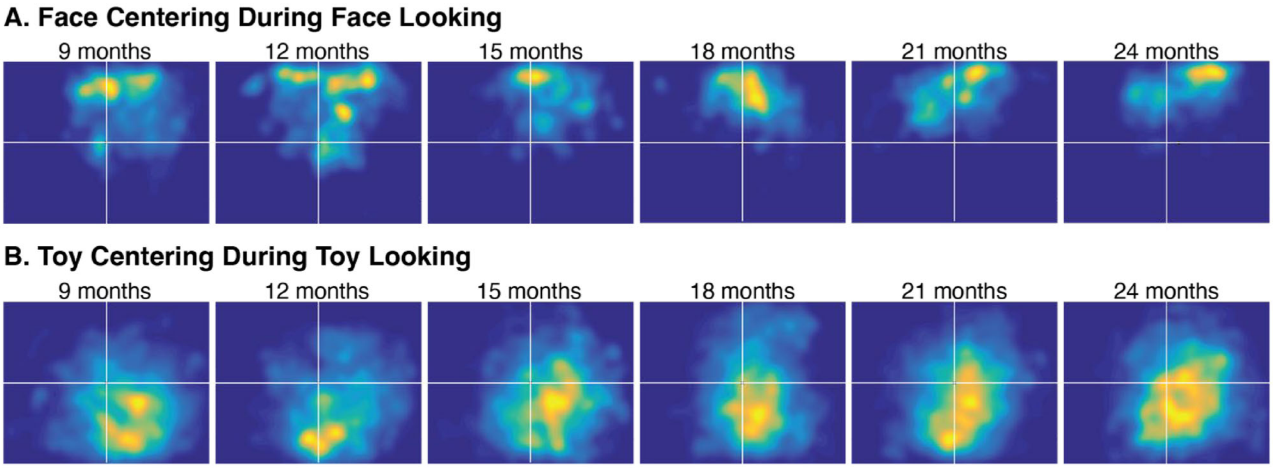

FIGURE 2 | Heatmaps showing density of (A) face and (B) toy locations in the FOV aggregated across infants in each age group at moments of face looking and toy looking, respectively. Toy locations are aggregated across the three toys. White lines indicate the horizontal and vertical centers of the FOV. With age, faces became increasingly less centered at moments of face looking, whereas toys became increasingly well centered during toy looking.

Time series of face locations were extracted for each session in FOV pixel coordinates at 30 frames/s. In total, 283,175 frames were coded across the 99 sessions. A reliability coder independently scored 400 frames for each session (~14% of the total data set). Agreement was high—correlations between coders were $r = 0.98$ for X coordinates, and $r = 0.93$ for Y coordinates. On average, discrepancies between coders were small (X coordinate: $M = 7.7$ pixels, $SD = 3.9$; Y coordinate: $M = 7.1$ pixels, $SD = 4.8$).

2.4.3 | Eye Movements and Target-Looking Episodes

After the session ended, the experimenter used Yarbus software to calibrate the eye-tracking data. Eye movement time series were calculated, with eye position *XY* coordinates (in pixels) indicating where infants looked within each FOV frame (yellow circle in Figure 1B). Eye movements were recorded at 30 frames/s. Moments where eye-tracking data were unavailable (e.g., blinks, eye movements outside of the trackable range of the system, or the software was unable to detect the pupil) were excluded from analysis ($M = 11.7\%$ of samples). To analyze whether eyes and head aligned to look at targets, we defined *looking episodes* for targets (toys and faces) when the gaze location was within 100 pixels of the toy/face center for greater than 2 consecutive frames. When multiple toys/faces were within 100 pixels, the closest toy/face to the gaze location was selected.

2.4.4 | Statistical Analyses

We tested each effect using linear mixed-effect models (LMMs) using the *lme4* (Bates et al. 2015) and *lmerTest* (Kuznetsova, Brockhoff, and Christensen 2017) packages in R. LMMs operate similarly to linear regressions but allow participants to contribute to different levels of a within-subjects factor without being dropped from analyses, facilitating analysis across infants who contributed data from different numbers of sessions. LMMs also allowed us to use the full time series data provided by participants rather than calculating by-participant means. Each model tested how centering varied according to different fixed effects and their interactions (i.e., age, target [face vs. toy], and holding). Random effects were included at the participant level; for each model, we attempted to fit maximal random intercept and slope terms and pruned random effects terms that prevented models from converging. Preliminary testing found no differences among the three toys, so toys were considered a single category. Age in months was treated as a continuous linear predictor in all models and was centered and scaled. Categorical predictors such as target (toy vs. face) and held (holding vs. not holding) were dummy coded and then mean-centered so that coefficients can be interpreted as main effects.

3 | Results

Our focal prediction was that infants would bias their view to align eyes and head while looking to favor toys rather than faces in the head-centered FOV. We report five analyses. First, we confirmed the assumption that infants would spend more time looking at toys compared with faces. Second, we tested the prediction that infants would better center toys in view (when looking at toys) at the expense of centering faces in view (when looking at faces). Both predictions were supported. The remaining analyses were designed to reveal what contributed to a bias for toys in the head-centered view at the moment of toy looking. We tested whether targets were better centered during longer versus shorter looks and whether held toys were better centered compared with non-held toys. Finally, we considered whether centering of all targets in view (not just the current gaze target) showed developmental change, which might suggest an overall shift in viewpoint by tilting the head down to better view toys compared with faces.

3.1 | Infants Spent More Time Looking at Toys Compared With Faces

First, we confirmed that the proportion of time that infants looked toys (aggregating across the three toys) was greater than time spent looking at caregivers' faces. Figure 3 shows that infants of all

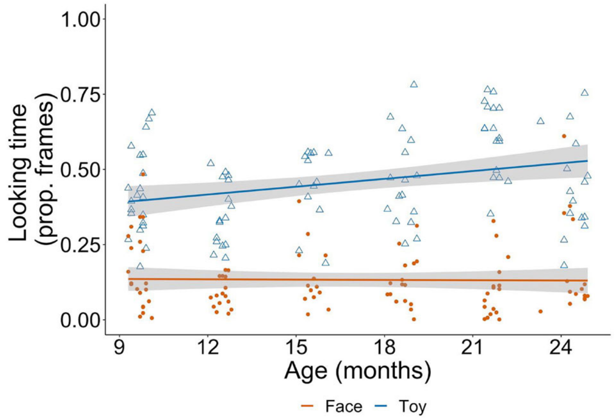

FIGURE 3 | Changes in total looking time (proportion of total video frames) toward caregivers' faces (orange circles) and toys (blue triangles) according to infants' age (*x*-axis). Toy looking represents the accumulated looking aggregated across all three toys. Each symbol represents one infant's mean face/toy looking during their monthly session. Lines with ±1 SE are smoothed conditional means.

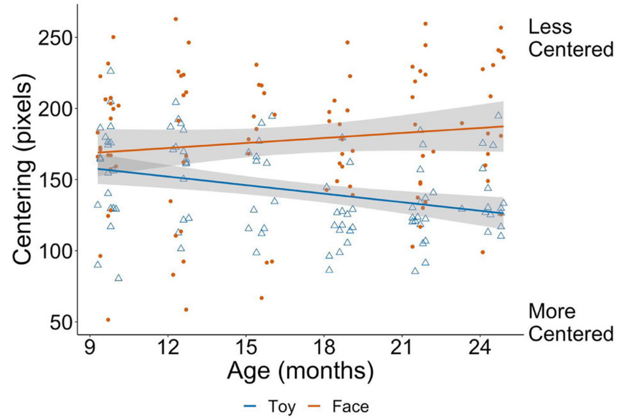

FIGURE 4 | Changes in centering (in pixels) of caregivers' faces (orange circles) versus toys (blue triangles) according to infants' age (*x*-axis). Smaller *y*-axis values indicate better centering with targets closer to the middle of head-centered field of view. Each symbol represents one infant's mean face/toy centering during their monthly session. Lines with ±1 SE are smoothed conditional means.

ages spent more time looking at toys (overall $M = 45.7\%$, $SD = 15.4$) compared with faces (overall $M = 13.3\%$, $SD = 11.4$), with older infants showing a widening gap between toy- and face-looking times. Toy-looking time increased from 35.3% at 9 months to 44.8% at 24 months; face looking was stable across age. An LMM with the formula *looking time* ∼ *age* × *target* + (1|*participant*) confirmed a significant *age* × *target* interaction ($b = 0.05$, $t = 2.52$, $p = 0.013$), which moderated significant effects of age ($b = 0.02$, $t = 2.33$, $p = 0.021$) and target ($b = 0.32$, $t = 17.19$, $p < 0.001$). Thus, for infants of every age, toys received greater attention compared with faces.

3.2 | Centering to the Most Task-Relevant Information

After establishing that toys were more frequently attended than faces, we can ask whether infants biased their eye-head alignment to favor toys versus faces. We predicted that (1) infants would be biased to center toys rather than faces in view because toys were more task relevant (based on greater attention), and (2) centering task-relevant information (toys) would improve with age. Distance to center (in pixels) was the measure of centering, with smaller numbers indicating targets were better centered in the FOV. We tested these predictions with an LMM with the formula *centering* ∼ *age* × *target* + (1 + *age* + *target*|*participant*); full model results are shown in Table 1. Figure 4 indicates that at 9 months, centering was similar for both faces and toys at the moment of looking at each target type: Faces averaged $M = 174$ pixels ($SD = 46.16$) from center, and toys averaged $M = 155.5$ pixels ($SD = 35.83$) from center. However, by 24 months, infants show a biased view: They center toys at the expense of centering faces. For 24-month-olds, faces averaged $M = 193$ pixels ($SD = 46.73$) from center and toys averaged $M = 139.2$ ($SD = 25.1$). The significant *age* × *target* interaction confirmed that older infants increasingly biased their view to center toys rather than faces. Lacking a significant effect of age suggests that this improvement does not come as a developmental improvement in centering in

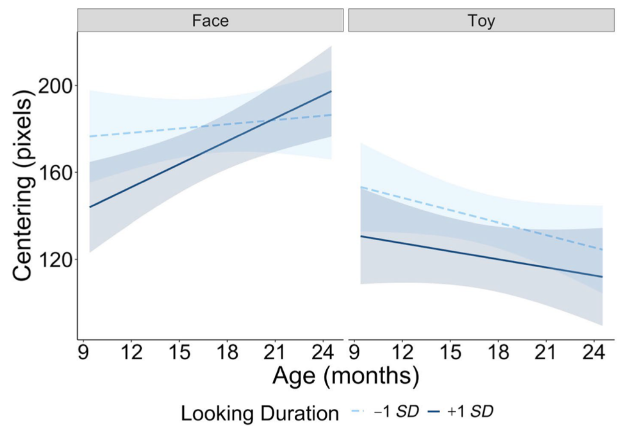

FIGURE 5 | Model interaction plot illustrating the three-way interaction among infants' age (*x*-axis), target type (face vs. toy in separate panels), and looking duration on centering. Dark blue lines indicate longer looks (+1 *SD*), whereas light blue lines indicate shorter looks (−1 *SD*). Shaded bands indicate 1 SE around the mean.

general but rather reflects a change in how infants navigate the trade-off among centering targets in different physical locations.

3.3 | Centering Relates to Look Duration

We predicted that if centering supports sustained attention to targets or if sustained attention supports centering, targets should be better centered during longer looking episodes compared to shorter looking episodes. We added looking duration to the previous model to investigate whether it played a role in centering, *centering* ∼ *age* × *target* × *look duration* + (1 + *age* + *target* + *look duration*|*participant*). Look duration (s) was a continuous predictor, mean-centered, and scaled. Table 2 shows the full model results. As expected, a significant effect of looking duration indicated that infants better centered targets in view during longer compared with shorter looking episodes. Moreover, Figure 5

TABLE 1 | Linear mixed-effect results for a model predicting centering (in pixels, with smaller values indicating better centering) based on age (in months), mean-centered target (face and toy), and their interaction.

Parameter	Fixed effects				Random effects
	Coefficient	*SE*	*t*	*p*	*SD*
(Intercept)	143.53	5.16	27.84	**<0.001**	30.33
Age	−4.50	5.49	−0.82	0.412	32.35
Target	−45.43	7.25	−6.27	**<0.001**	45.58
Age × *target*	−20.72	0.46	−45.14	**<0.001**	

Note: The maximal model to converge was *centering* ~ *age* × *target* + (1 + *age* + *target*|*participant*). Data for this analysis were face and toy locations only at moments when they were looked at. Bold denotes *p* values < 0.05.

TABLE 2 | Linear mixed-effect results for a model predicting centering (in pixels, with smaller values indicating better centering) based on age (in months), mean-centered target (face and toy), looking duration, and all fixed effect term interactions.

Parameter	Fixed effects				Random effects
	Coefficient	*SE*	*t*	*p*	*SD*
(Intercept)	144.50	5.22	27.71	**<0.001**	30.66
Age	−4.39	5.60	−0.78	0.433	33.02
Target	−44.83	7.00	−6.41	**<0.001**	43.97
Look duration	−7.09	2.26	−3.14	**0.002**	14.13
Age × *target*	−16.22	0.49	−32.98	**<0.001**	
Age × *look duration*	2.73	0.22	12.29	**<0.001**	
Target × *look duration*	−3.06	0.44	−6.93	**<0.001**	
Age × *target* × *look duration*	−4.99	0.40	−12.58	**<0.001**	

Note: The maximal model to converge was *centering* ~ *age* × *target* × *look duration* + (1 + *age* + *target* + *look duration*|*participant*). Bold denotes *p* values < 0.05.

shows interaction effect plots to visualize the significant three-way interaction, which revealed that the relation between age and look duration differed between faces (left plot) and toys (right plot). For faces, a follow-up analysis indicated that age and looking duration interacted ($b = 6.06$, $t = 17.62$, $p < 0.021$), with younger infants showing better centering of faces during long looks, but no difference between longer and shorter face looks among older participants. For toys, infants of all ages centered toys better during longer compared with shorter looks ($b = -6.68$, $t = -2.54$, $p = 0.016$), but age and look duration did not significantly interact ($p = 0.064$).

3.4 | Toy Centering is Not a Consequence of Toy Holding

Next, we asked whether the centering of toys was related to infants' manual action. Possibly, the increasing bias in centering toys with age could reflect improvements in the visual control of toy manipulation if alignment of eyes and head support manual control. To test this, we conducted an analysis of whether infant holding was related to centering, restricting the analysis to toys (excluding faces) because faces could not be held. The final model was *centering* ~ *age* × *holding* + (1 + *age* + *holding*|*participant*), which is reported in Table 3. The only significant result to emerge was that held toys were less centered on average ($M = 163.4$ pixels, $SD = 40.91$) compared to toys that were not held ($M = 133.9$, $SD = 32.61$), contrary to our prediction. This indicates that the development bias toward centering toys cannot be explained by differences in manual behavior.

3.5 | Toy Centering May Result From a General Shift in Viewpoint

Up to this point, our analyses have exclusively tested the location of targets in the FOV at the moment they are looked at—faces during face looking and toys when that particular toy was the infant's focus of attention. In the final analysis, we asked whether non-gaze targets (such as the face, green toy, and blue toy in Figure 1B during a look toward the red toy) also showed a change in centering. If infants increasingly orient their heads down toward toys, even toys that are not currently looked at would show a centering improvement if there is a general change in viewpoint. We repeated the centering analysis, *centering* ~ *age* × *target* + (1 + *age* + *target*|*participant*), using only video frames in which faces/toys were not looked at. Table 4 shows that the pattern of results was identical to the earlier analysis of centering during looking: With age, toys became better centered compared with faces. This result reveals a general age-related bias for older infants that improves the centering of all toys in view at the expense of faces, likely as the result of infants adopting a downward head angle. An alternative, but unlikely, possibility is that all targets (toys and faces) changed their

TABLE 3 | Linear mixed-effect results for a model predicting centering of toys (in pixels, with smaller values indicating better centering) based on age (in months), mean-centered toy holding (not holding and holding), and their interaction.

Parameter	Fixed effects				Random effects
	Coefficient	*SE*	*t*	*p*	*SD*
(Intercept)	199.45	4.73	42.17	**<0.001**	27.88
Age	−6.21	4.71	−1.32	0.187	27.96
Holding	10.73	4.53	2.37	**0.018**	28.61
Age × *holding*	−0.11	0.31	−0.35	0.725	

Note: The maximal model to converge was *centering* ∼ *age* × *holding* + (1 + *age* + *holding*|*participant*). Bold denotes *p* values < 0.05.

TABLE 4 | Linear mixed-effect results for a model predicting centering (in pixels, with smaller values indicating better centering) based on age (in months), mean-centered target (face and toy), and their interaction during non-looking episodes.

Parameter	Fixed effects				Random effects
	Coefficient	*SE*	*t*	*p*	*SD*
(Intercept)	218.07	5.59	38.99	**<0.001**	32.89
Age	−2.52	5.04	−0.50	0.618	29.64
Target	−21.04	5.58	−3.77	**<0.001**	35.26
Age × *target*	−14.71	0.27	−55.19	**<0.001**	

Note: The maximal model to converge was *centering* ∼ *age* × *target* + (1 + *age* + *target*|*participant*). Data for this analysis were face and toy locations only at moments they were not looked at. Bold denotes *p* values < 0.05.

location relative to older versus younger infants independent of the infants' own actions; a more parsimonious interpretation is that a change in infants' head position accounts for the difference in overall centering.

4 | Discussion

The current study revealed how infants' head-centered view aligns to different visual targets competing for infants' attention. Younger infants' views were unbiased, with toys and faces centered equally in view during looking. Consistent with our hypothesis, we found that older infants increasingly biased their viewpoints to favor toys over faces, improving the alignment of eyes and head to toys at the moment of looking. Older infants' bias to orient toward toys was most likely accomplished by tilting their heads down, which centered toys in view even for moments when toys were not looked at. Head orientation is related to sustained attention, with better orienting found for targets of longer looking episodes. Yet, this could not explain the developmental changes in orienting, because even 9-month-olds showed improved centering during longer looks. Moreover, the developmental change in toy centering was not a byproduct of manual control; to the contrary, held toys were significantly less centered in view compared with toys that were not held.

Everyday visual scenes are complex and cluttered. At any given moment, observers must orient their visual attention toward one location at the exclusion of others. Replicating past work in infant triadic play, we found that infants asymmetrically distribute their attention to toys over caregivers' faces (Deak et al. 2014; Franchak, Kretch, and Adolph 2018; Yu and Smith 2013). From 9 to 24 months, toys increasingly drew infants' attention. The current study goes a step farther to reveal how different targets are aligned in the head-centered FOV. At 9 months, infants spent longer amounts of time looking at toys compared to faces. However, despite this bias in looking *time*, there was no corresponding bias in *eye–head alignment*: Younger infants showed similar alignment to toys and faces. By 24 months, older infants' eye–head alignment favored toys at the expense of faces (matching their overall bias in time spent looking toward toys vs. faces). We do not mean to suggest, however, that this is a conscious strategy choice, but rather that older infants have discovered a more efficient way to coordinate visual attention within the confines of this task.

Although the results supported our overall hypothesis—that task-specific orienting would improve with age—our analyses about why this would change with age did not conclusively implicate either sustained attention or manual control. Attention can be directed briefly and casually to an object (i.e., a quick glance), or it can be effortfully sustained on an object for a longer duration (Ruff and Lawson 1990; Suarez-Rivera, Smith, and Yu 2019). Sustained attention increases substantially during late infancy and early childhood as children engage in longer episodes of looking to objects during play (Ruff and Capozzoli 2003; Ruff and Lawson 1990; Ruff et al. 1990). We reasoned that because sustained attention increases with age, we might observe an interaction such that older infants show better centering during longer looks. However, we found that centering was better during longer looks for infants of every age. Because of the correlational nature of the analysis, it is unknown whether longer looking facilitates centering and/or centering facilitates longer looking. Regardless, the only age-related result is that older infants showed a *decrease in centering faces* during longer face-looking episodes. For toys, older infants showed better centering during both longer and shorter looks compared with younger infants (looking duration and age did not interact). Thus, improvements in sustained attention are unlikely to explain why toy looks in particular showed better centering with age.

A second potential explanation was that the role of vision in controlling manual action may provide an impetus for infants to bias their view toward toys over faces. Aligning the head resolves mismatches among spatial frames of reference that prevents interference (Biguer, Prablanc, and Jeannerod 1984) and may help stabilize gaze on moving targets while reaching (Bertenthal and von Hofsten 1998) or manipulating objects. But contrary to our prediction, objects that were held in infants' hands were overall less centered in view compared with non-held objects. Most likely, infants spent more time holding objects down and close to their bodies and the table rather than raising them high in the visual field. Non-held toys resting on the table might have been easier to center in view if they were higher in the visual field. Likewise, objects held in caregivers' hands might also facilitate infants' attention (Deak et al. 2014; Yu and Smith 2013, 2017a,b). Prior work shows that caregivers' hands are often higher in view compared with infants' hands, so toys held by caregivers might have an advantage for centering (Bambach et al. 2014). An alternative explanation is that holding toys provides nonvisual exploratory information (e.g., tactile, proprioceptive), which may have reduced the demand to center objects in view. Regardless, changes in holding could not explain why toys became better centered in view with age.

Possibly, other aspects of visual–manual control could still contribute. We analyzed eye–head alignment at moments of holding but did not score when infants were reaching to an object. At the onset of reaching, young infants fail to use visual feedback about the position of the hand relative to objects while reaching (Babinsky, Braddick, and Atkinson 2012; Clifton et al. 1994). By 15 months, visual feedback improves reaching performance (Carrico and Berthier 2008). Although the relation between reaching performance and visual guidance is less stable during natural reaching in 18- to 24-month-olds, infants frequently align their eyes to objects while reaching (Franchak and Yu 2015).

Another possibility is that because older infants spent more overall time looking at toys, they might have spent less time looking back and forth between faces and toys and more time switching gaze between toys. If so, they might have kept their heads tilted down for longer periods of time, making it easier to center toys in view after switching gaze between them. This is consistent with the final result—that toys were better centered even during non-looking moments. Although we did not directly measure head position, the latter result is most likely the result of older infants tilting their heads down as opposed to all three objects moving relative to the observer. Furthermore, we emphasize that control of the visual system depends on a nested system of the eyes within the head within the body. Without independent measures of the head and trunk, we cannot separate out how postural control versus head orientation explain the current pattern of results, given that both have been shown to contribute to gaze stabilization in prior infant work (Borjon et al. 2021). Possibly, age differences in postural control may relate to differences in centering visual targets. Seven-month-olds reduce postural sway by a greater amount to look at an externally presented toy compared to a toy held in their own hands (Arnold et al. 2020). Even while sitting in a highchair, the demands of stabilizing the trunk to look—especially when switching between multiple toys and the caregivers' face—may be more taxing for the youngest infants thus resulting in worse centering.

Future work is needed to test whether infants bias their views in tasks other than supported seated play with caregivers and objects. A large body of work on naturalistic eye movements demonstrates that looking patterns vary widely according to task (Foulsham, Walker, and Kingstone 2011; Franchak and Adolph 2010; Franchak, Kretch, and Adolph 2018; Hayhoe et al. 2003; Land 2006; Land and Hayhoe 2001; Land, Mennie, and Rusted 1999; Pelz, Hayhoe, and Loeber 2001). In the current study, we found that infants biased their view toward toys over faces, but we expect this pattern is due to the demands of the task, in which toys were novel and caregivers were encouraged to use the toys to play with infants. Additionally, more work is needed to understand what specific aspects of faces and toys led to the observed results in this task. Faces are social, are looked at infrequently, are not easily manipulated with the hands, and are located at the top of infants' view; the current study only tested a familiar caregiver's face. In contrast, toys are not inherently social, are looked at frequently, are prime targets for manual action, and are located at the bottom of infants' view; the current study only tested novel toys. Varying targets across these dimensions will reveal which aspects are most strongly related to a biased viewpoint. On the basis of growing evidence suggesting that older infants' and toddlers' visual attention is directed in a top-down way to reflect their tasks and goals (Kadooka and Franchak 2020; Kwon et al. 2016; Tummeltshammer and Amso 2018), we suspect that the current results are not fundamentally about toys versus faces, but about how infants' head alignment reflects infants' visual attention to different targets. In a task that might prioritize face looking (such as with an unfamiliar adult, or in a situation where faces are motorically easier to view), infants may increase the amount of time they look at faces and also keep faces more centered in view. To put it differently, we believe the current results reflect infants' self-selected prioritization of what and where to attend.

In conclusion, the current study adds to the growing body of work that emphasizes embodied effects on infants' visual experiences (Bambach, Crandall, and Yu 2013; Bambach et al. 2016; Fang et al. 2015; Fogel et al. 1999; Franchak, Kretch, and Adolph 2018; Franchak et al. 2011; Kretch, Franchak, and Adolph 2014; Schillingman et al. 2015; Yu and Smith 2013) by showing how head alignment within a posture shape what infants see. The development of a biased viewpoint suggests that infants are learning how to use motor abilities to make visual exploration more efficient, which may contribute to burgeoning attentional skills (Colombo 2001; Ruff and Capozzoli 2003). Furthermore, changes in how the motor system shapes visual exploration will differentially filter inputs for learning experienced in daily life, with the possibility of cascading effects on other aspects of development (Franchak 2020a; Oakes 2017). A more complete picture of the development of eye, head, and body movements that support visual selection and how those movements are coordinated between and within different postures is needed to understand infants' visual experiences in everyday life.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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