Exploring Developmental Change in Ego-Motion Experience Across Infancy

by

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ABSTRACT

Humans flexibly and intuitively use vision to plan and guide navigation through the local environment. How does this ability develop in infancy? One possibility is that the development of visual representations for navigation is driven by passive exposure to the visual statistics of scenes. Another possibility is that active navigation experience using vision to plan and guide locomotion is the driving factor. In order to distinguish between these two hypotheses, it is necessary to understand the nature of infants' early visual scene experience itself. Surprisingly little prior work has characterized infants' early experiences with ego-motion through scenes, before and after learning to locomote. We use ecological momentary assessments to quantify infants' exposure to ego-motion through scenes, and how that changes with locomotor experience. We found that pre-crawling infants who have never independently navigated already experience significant passive visual exposure to forward-facing ego-motion through scenes. Nevertheless, this experience increases substantially with age and locomotor status.

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Acknowledgments

First, I would like to express my sincere gratitude to Freddy for his exceptional mentorship and guidance throughout my time as both a UROP and a member of the Saxelab during my MEng program. His resourcefulness, intellectual curiosity, and encouragement have played a pivotal role in shaping me both as a scientist and as an individual. Working alongside Freddy has been an incredible privilege, and I am truly grateful for the opportunity to contribute to his remarkable research.

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1 Introduction

The ability to use vision to plan and guide navigation through the local visual environment, or "scene", is crucial to survival. By childhood and adulthood, humans accurately use vision for navigation. How does this ability emerge? There is a longstanding debate about whether and how visuo-spatial and navigational abilities are biologically predisposed, and the role of visual, motor and navigation experience in their development [1][2]. One hypothesis is that visual representations for navigation develop in response to passive visual experience, emerging slowly with exposure to the visual statistics of scenes. A second hypothesis is that visual representations for navigation develop in response to active navigation experience (i.e., the onset and development of independent locomotion).

To distinguish these hypotheses, a key premise is that visual representations for navigation only become relevant when infants gain the ability to navigate independently, typically by learning to crawl [3] [4]. The onset age of crawling is enormously variable: infants start crawling between 5 and 11-months of age – a difference of 100% of their lifespan! Existing behavioral evidence clearly suggests that the onset of independent navigation changes the functional relevance of visual scenes. For example, converging evidence across studies using age-held-constant designs, walker manipulations, motorically delayed infants, and lag-sequential longitudinal investigations has demonstrated a crucial role for active navigation in the development of navigational affordances (e.g., in the visual cliff paradigm) in humans [5] [6] [7] mirroring classic work in kittens [8] [9] [10]. Navigation affects infants' ability to use peripheral scene information for postural control (i.e., in the moving room paradigm) [11]

[12], visual search strategies (i.e., "object permanence") [13] [14], and memory for allocentric locations and environmental landmarks [15] [16]. Crawling experience also predicts infants' neural responses while watching other infants crawl [17]. Across these domains, the use of optic flow information depends on the duration of locomotor experience, not chronological age, and these effects emerge within just a few weeks of locomotor experience [18].

This prior evidence suggests that experience actively navigating may be more important than passive visual experience of optic flow through scenes, in generating the visual representations for navigation. However, there is a striking gap in knowledge: almost no research has quantified infants' passive experience of visual scene statistics before they begin to crawl, or how crawling onset changes visual experience of scenes. Independent navigation creates visual patterns associated with ego-motion through a scene — but so does being passively moved (e.g. in a stroller, car seat, carrier or someone's arms). The extent of infants' experience with self- and other-powered ego-motion has never, to our knowledge, been measured. One study of ten American and ten Indian infants, aged between 2 and 15 months, found that infants in both cultures experienced motion through scenes at all ages, and that patterns of optic flow are similar, while speed and frequency of motion are affected by individual and cultural differences [19]. However, this study did not isolate the effect of locomotor experience. It is therefore possible that infants only gain substantial experience with forward-facing, ego-motion (i.e., the critical visual experience of navigation) after learning how to crawl or walk. If so, then the two developmental hypotheses make similar predictions with regard to the time course of developmental change.

To study infant experience, there are two common approaches. The first approach is by utilizing headcam data. While headcam data provides rich data of visual scene statistics, there are also serious limitations: it is challenging to fully randomize the time of data collection [20] potentially biasing footage toward systematic, repeated contexts, and the sample of infants with headcam data is typically very small. Furthermore, head cameras are too heavy for younger infants, especially those 6 months and younger, meaning that pre-navigation ages are potentially missed entirely. Addressing these issues, we decided to use the second approach: Ecological Momentary Assessment (EMA) [21]. EMA is better adapted for providing a representative description of infant experience as it is inexpensive, easily accessible, and affords the experimenter better control over the timepoints that are sampled, allowing an accurate assessment of typical daily experience [21][22][23]. During our study, participants were sent a short survey via text message 3 times a day, at random timepoints between 6am and 6pm, for 5 consecutive days. The survey included 8 questions about the child's current or most recent ego-motion experiences. These questions covered if and how the child was moving and for how long. We recruited infants and toddlers ages 0 to 18 months old. This age range was chosen as it spans the range of active navigation abilities, from infants who cannot move their own bodies at all to proficiently walking infants who can navigate for many consecutive meters.

2 Methods

2.1 Sample Size

In order to study how ego-motion experience changes across the onset of active navigation ability, including the earliest experiences of active navigation (typically by crawling), as well as the onset and development of walking, we recruited infants and toddlers ages 0 to 23-months. We first recruited a pilot sample of 22 infants and toddlers, in order to explore trends and plan confirmatory analyses. While the final sample consisted of 290 participants and 3483 total responses, we were able to use data from 271 participants and their 3261 responses (Figure 2.1). The final sample size was chosen based on the amount of data that was possible to collect prior to thesis deadlines for key personnel. In ongoing work, we are collecting additional data around the time of walking onset, between 9 and 14 months old.

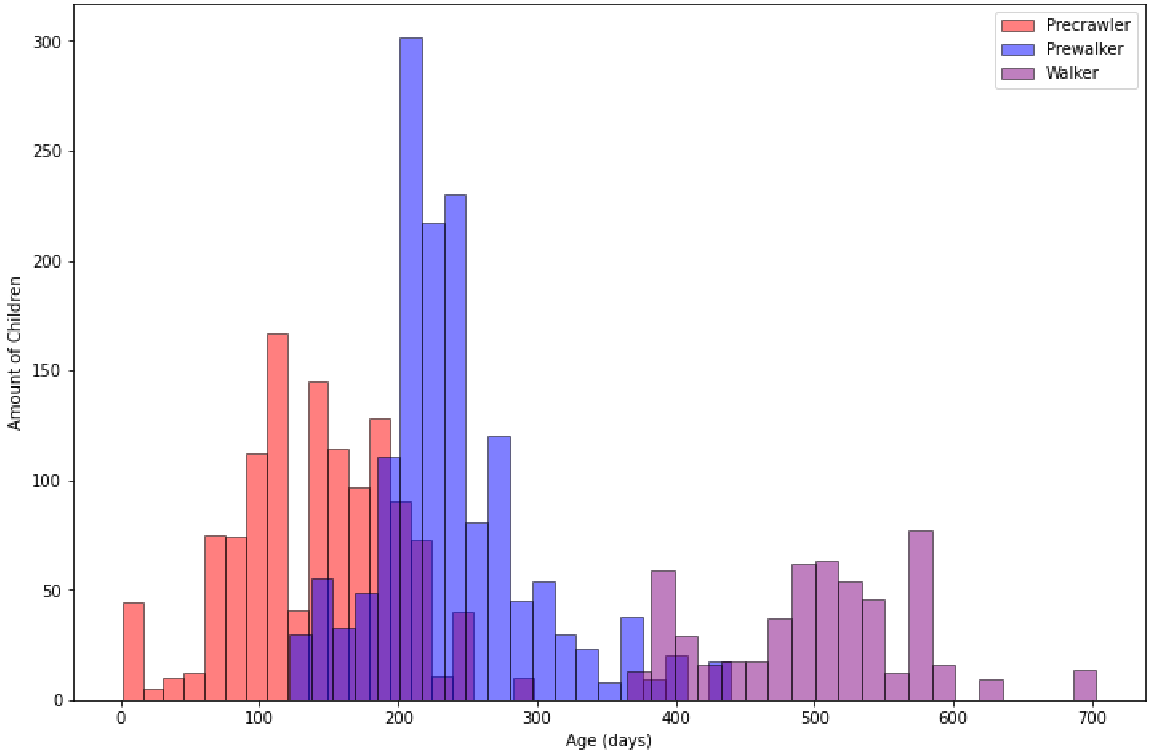

Figure 2.1: Age Distribution of participants. Precrawler (N=106, red bars): Age range is 0-298 days, or 0-10 months. Prewalker (N=124, blue bars): Age range is 121-440 days, or 4-15 months. Walker (N=41, purple bars): Age range is 365-705 days, or 12-23 months.

2.2 Participant Age

The mean age of the final sample was 7.8 months (Range = 0-23 months, N = 137 male, N = 139 female). Infants ages 6-9 months old were overrepresented in order to aid dissociation of age and crawling experience, which occurs variably in this range. Infants and toddlers were categorized into three different locomotor groups: precrawlers (who have never independently navigated by any means to a location more than 3 feet away), prewalkers (who are capable of independent navigation by any means other than walking), and walkers (who are capable of navigating via bipedal locomotion). Parents of infants were recruited via online advertisements (e.g., on Facebook), word of mouth, and the Children Helping Science/Lookit platform. Many infants also participated in other ongoing experiments in our lab testing infants' and toddlers' perception of navigational affordances.

2.3 Procedure

We used a survey-based EMA approach to inquire about participants' current navigational experience at 3 random times a day, for 5 consecutive days (15 total surveys per participant). The surveys were hosted using Alchemer.com, and were sent out through an EMA platform, Surveysignal, which automated the timing of text messages to participants. Prior to participating in our study, parents filled out our Movement Ability Questionnaire (MAC) survey covering children's major locomotor milestones, including crawling and walking, and for infants who had begun crawling and/or walking, the parents estimate of the day they started crawling and/or walking. Once the MAC was completed, participants began receiving the pseudorandomly timed text messages with survey links. Parents were asked to fill out the survey as soon as they receive it and respond to the best of their ability. Parents could choose whether or not to participate in a given survey, but we encouraged parents to fill it out even if they were not with their child, and to simply select "No" to the question "Are you with your child right now?" Participants were compensated with a $15 Amazon gift card for their time. The instructions, questions, and answer choices found in this survey were as follows: Please complete the following questionnaire concerning your child's current activity. This questionnaire has been designed for a wide range of situations and ages. Therefore, it is possible that your child is currently performing few, some, or many behaviors relevant to the questions listed below. Please answer questions as accurately as you can. If you do not know the answer to a question, simply respond or indicate "uncertain."

2.3.1 EMA Survey

#	Question	Response Options
1	Are you with the child right now?	Yes, No
2	Is the child awake right now?	Yes, No
3	In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?	Yes, No, Uncertain
4	Think of the most recent time you saw the child awake and moving through the environment.Please briefly describe the event (e.g., "I carried the infant from the bedroom to the kitchen", or "the infant was crawling around on the living room floor").	Free response
5	Think of the most recent time you saw the child awake and moving through the environment. How long ago was that?	In the last 5 minutes, 5 to 30 minutes ago, More than 30 minutes ago
6	Think of the most recent time you saw the child awake and moving through the environment.Was the child controlling their own motion, or was someone/something else?	Someone/something else controlled their motion (e.g,. being carried or riding in a stroller or car), They controlled their own motion (e.g., by crawling or walking)
7	Think of the most recent time you saw the child awake and moving through the environment. Which direction was the child primarily looking while moving?	Forward, in the direction they were moving (e.g., while crawling, or riding in a front-facing stroller), Backwards, opposite the direction they were moving (e.g., in a rear-facing stroller), Uncertain or other
8	Last question! Think of the most recent time you saw the child awake and moving through the environment. How long was the child moving that way?	For a few seconds, For a few minutes, For ten minutes or more

Table 2.1: EMA Survey Questions and Responses

2.4 Exclusions

For all analyses, we completely excluded responses from participants that did not provide a date of birth or did not complete the Movement Ability Questionnaire (as required to determine age and locomotor status). We further excluded specific responses that were left empty or answered as "Uncertain" when exploring different dependent variables. For participants who indicated they were unsure of their child's locomotor ability, we further analyzed other motor ability questions and placed their child accordingly.

3 Analysis

3.1 Overall ego-motion experience

We began by quantifying awake, ego-motion experience in precrawling infants, and exploring how ego-motion experience changes with age and locomotor ability. To do so, we separated responses by locomotor group (precrawler, prewalker, walker), and calculated the percentage of responses where parents indicated "Yes" to both survey Q2 ("Is your child awake?") and Q3 ("Was your child moving in the last 5 minutes?"). We found that awake ego-motion was experienced in the last five minutes for 47.20% of precrawlers' responses, 57.74% of prewalkers' responses, and 62.29% of walkers' responses (values calculated without considering wakefulness are also shown in Figure 3.1). Comparing between groups, precrawlers experienced ego-motion 75.76% as often as walkers, and 81.73% as often as prewalkers. Prewalkers experience ego-motion 92.70% as often as walkers. These data suggest that ego-motion experience is abundant (i.e., present in 47.20% of 5-minute time windows sampled) even before infants ever learn to crawl or walk, but nevertheless increases with age and locomotor experience.

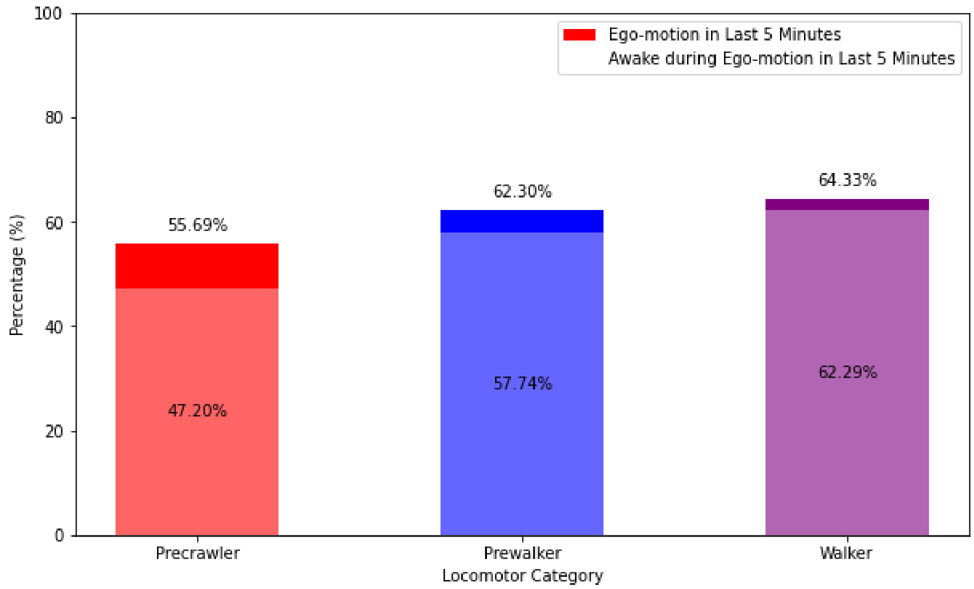

Figure 3.1: Results for overall ego-motion experience. Overall ego-motion experience was assessed based on responses to survey question 2 ("Is the child awake right now") and survey question 3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?"). Within each locomotor group, the percentage of "Yes" responses out of the total number of responses was plotted to show the overall ego-motion experience. Additionally, within each locomotor group, the percentage of time the response was both "Yes" to question 2 and question 3 was plotted in lighter colors on each bar. Precrawlers: "Yes" responses to Q3 = 695, "Yes" responses to Q2 and Q3 = 589, total responses = 1248. Prewalkers: "Yes" responses to Q3 = 917, "Yes" responses to Q2 and Q3 = 850, total responses = 1472. Walkers: "Yes" responses to Q3 = 348, "Yes" responses to Q2 and Q3 = 337, total responses = 541.

To better understand developmental change in overall ego-motion experience, we next tested whether differences between the groups above are explained by age, locomotor experience, or both. We fit a logistic mixed effects regression model (using the lme4 package v1.1.33 in R) with the expression:

$$\text{lmer}(yes\_motion\_last\_5min \sim age + precrawling + (1|subject))$$

The outcome variable $yes\_motion\_last\_5min$ was based on survey Q2 and Q3, with responses coded as 1 if both questions were "Yes" (reflecting awake, ego-motion experience) and 0 if either or both answers were "No". Age values were expressed as days of age at the time of response and z-scored. The precrawling variable was one-hot encoded (i.e., 1 for "precrawlers", 0 for "prewalkers" and "walkers"). Prewalkers and walkers were treated as the reference category. We originally considered walking status in addition to precrawling, but found walking status and age to be highly collinear; walking was therefore dropped from the model. This analysis revealed significant change with age ($p < 0.01$, $z = 3.23$, 95% CI = [0.063, 0.25]) and precrawler status ($p < 0.01$, $z = -2.80$, 95% CI = [-0.47, -0.11]) (Figure 3.2).

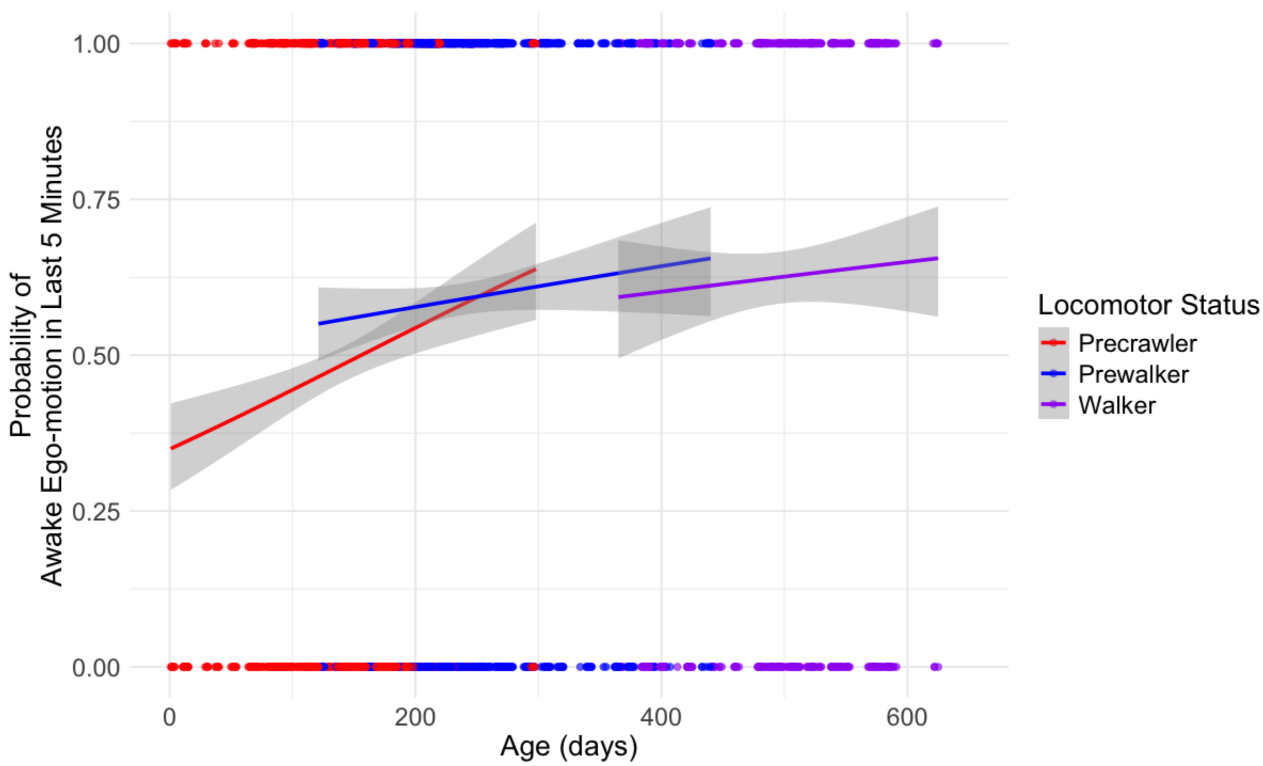

Figure 3.2: Results for age- and locomotor-related increases in overall wakeful ego-motion experience. Overall ego-motion experience was assessed based on responses to survey question 2 ("Is the child awake right now") and survey question 3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?") . yes_motion_last_5min was coded as 1 if both question 2 and question 3 were "Yes" responses, and coded as 0 for all other response combinations. The predicted probability of selecting yes_motion_last_5min being 1, as determined via logistic regression, is shown on the y-axis. Individual responses are indicated by colored markers, where colors correspond to locomotor group membership. Shaded areas indicate 95% confidence intervals.

3.2 Other-powered versus self-powered motion

What proportion of the overall ego-motion experience above comes from self-powered versus other-powered ego-motion? By definition, precrawling infants are not capable of self-powered motion, but the relative balance of self- and other-powered ego-motion after locomotor onset – and how that changes with age and locomotor experience – is unknown. To address this question, we analyzed the subset of survey responses where parents indicated "Yes" to survey Q2 ("Is your child awake?") and Q3 ("Was your child moving in the last 5 minutes?"). Then, we used survey Q6 to calculate the proportion of ego-motion responses indicated as "They controlled their own motion", out of the total responses given with each respective group. We found that prewalker's ego-motion experiences were 51.47% self-powered, while walker's ego-motion experiences were 82.49% self-powered. Fundamentally, precrawlers's self-powered ego-motion experience should be 0%. However, there were parents that indicated their precrawlers controlled their own motion for 11.88% of responses, suggesting either misunderstanding or mistakes in filling out the questionnaire (Figure 3.3).

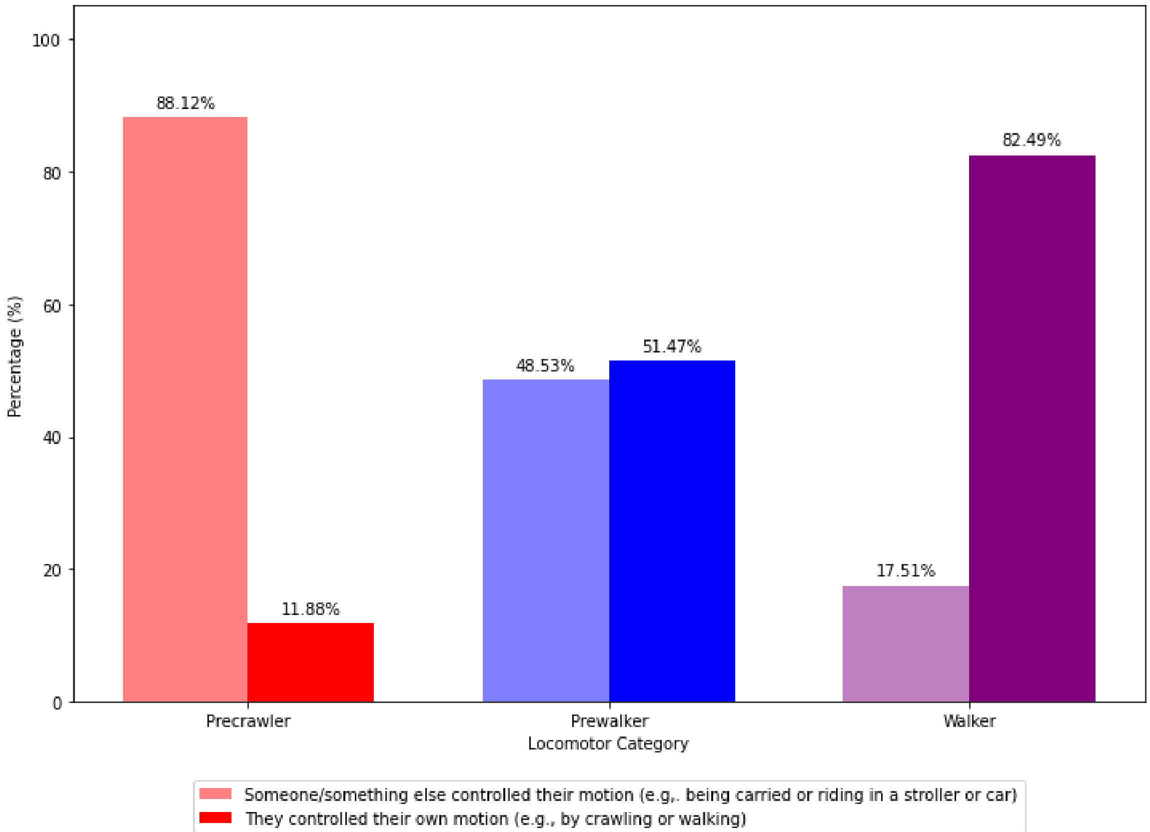

Figure 3.3: Results for other-powered versus self-powered ego-motion experience. Overall ego-motion experience was assessed based on responses to survey Q2 ("Is the child awake right now"), Q3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?"), and Q6 ("Think of the most recent time you saw the child awake and moving through the environment. Was the child controlling their own motion, or was someone/something else?"). We took the subset of responses that were "Yes" for question 2 and question 3, and for each locomotor group, calculated the percent of time the child was experiencing other-powered ego-motion (the left bar, lighter colors), and self-powered ego-motion (the right bar, darker colors), as described in the text. Precrawlers: "Self-powered" responses = 519, "Other-powered" responses = 70, total responses = 589. Prewalkers: "Self-powered" responses = 412, "Other-powered" responses = 437, total responses = 849. Walkers: "Self-powered" responses = 59, "Other-powered" responses = 278, total responses = 337.

Next, to investigate how self-powered versus other-powered ego-motion experience changes with age and locomotor experience, we fit a logistic mixed effects regression model with the expression:

$$\text{lmer}(selfmotion \sim age + precrawling + (1|subject))$$

This analysis was conducted on the subset of responses in which parents indicated that their child was awake (i.e., "yes" on survey Q2) and had experienced ego-motion in the last five minutes (i.e., "yes" on survey Q3). The outcome variable $selfmotion$ was based on survey Q6, with responses coded as 1 for "they controlled their own motion" and 0 for "someone/something else controlled their motion". Age values were expressed as days of age at the time of response and z-scored. The precrawling variable was one-hot encoded (i.e., 1 for "precrawlers", 0 for "prewalkers" and "walkers"). We originally considered walking status in addition to precrawling, but found walking status and age to be highly collinear; walking was therefore dropped from the model as an independent variable. Prewalkers and walkers were treated as the reference category. This analysis revealed significant change with age ($p < 0.001$, $z = 6.53$, 95% CI =[0.62, 1.15]) and significant change with precrawlers ($p < 0.001$, $z = -7.38$, 95% CI = [-2.81, -1.68]) (Figure 3.4).

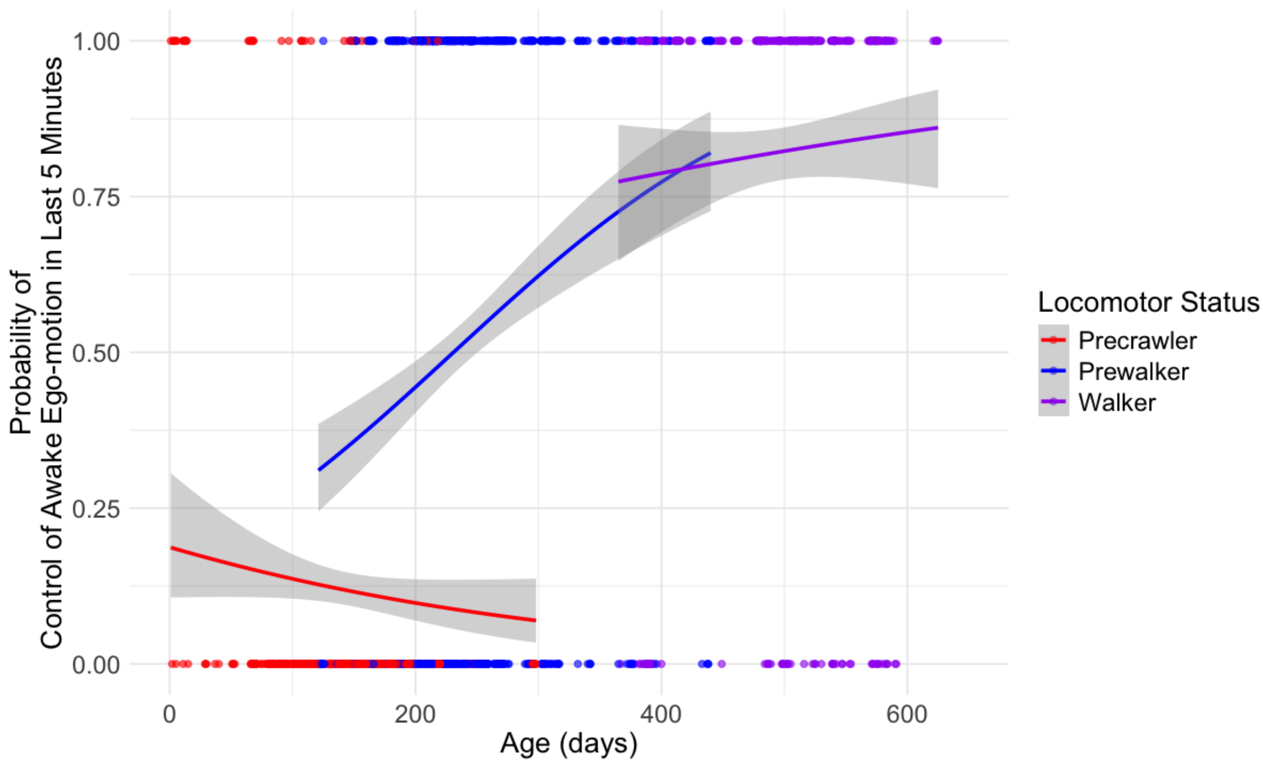

Figure 3.4: Results for age- and locomotor-related increases in other- versus self-powered ego-motion experience. Ego-motion experience was assessed based on responses to survey Q2 ("is your child awake"), Q3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?") and Q6 ("Think of the most recent time you saw the child awake and moving through the environment. Was the child controlling their own motion, or was someone/something else?"). On the y axis, values of 1 indicate self-powered motion, while values of 0 indicate other-powered motion. Trend lines indicate the probability of self-powered motion with age, as determined through logistic mixed-model regression, described in the text. Individual responses are indicated by colored markers, where colors correspond to locomotor group membership. Shaded areas indicate 95% confidence intervals.

3.3 Facing direction during ego-motion

Although our results above show that infants gain substantial experience with ego-motion prior to the onset of locomotion, this ego-motion experience is entirely other-powered, and thus potentially differs substantially from the ego-motion experienced at later ages, after infants have learned to crawl and walk. We next performed a series of analyses aimed to better understand the nature of this early visual experience, and the extent to which it provides visual input similar to that experienced by older, walking toddlers. A first possibility is that pre-crawling ego-motion experience differs in the facing direction of motion. Whereas proficient, self-powered locomotion is almost always experienced facing forward, it is possible that early, other-powered motion is often experienced backward. To quantify the extent of forward versus backward ego-motion experienced in pre-crawling infants, relative to older locomotor groups, we analyzed the subset of survey responses in which parents indicated "Yes" to survey Q2 ("Is your child awake?") and Q3 ("Was your child moving in the last 5 minutes?"). For each locomotor group, we used survey Q7 to calculate the proportion of ego-motion responses indicated as "forward motion", out of the total responses within each respective group. We found that precrawlers experienced forward-facing ego-motion for 48.56% of their awake ego-motion experiences, 75.53% for prewalkers' awake ego-motion experiences, and 92.22% of walkers' ego-motion experiences. These results therefore suggest that even pre-crawling infants experience substantial forward-facing motion, but that the relative extent of forward vs. backward facing ego-motion nevertheless shifts with development (Figure 3.5).

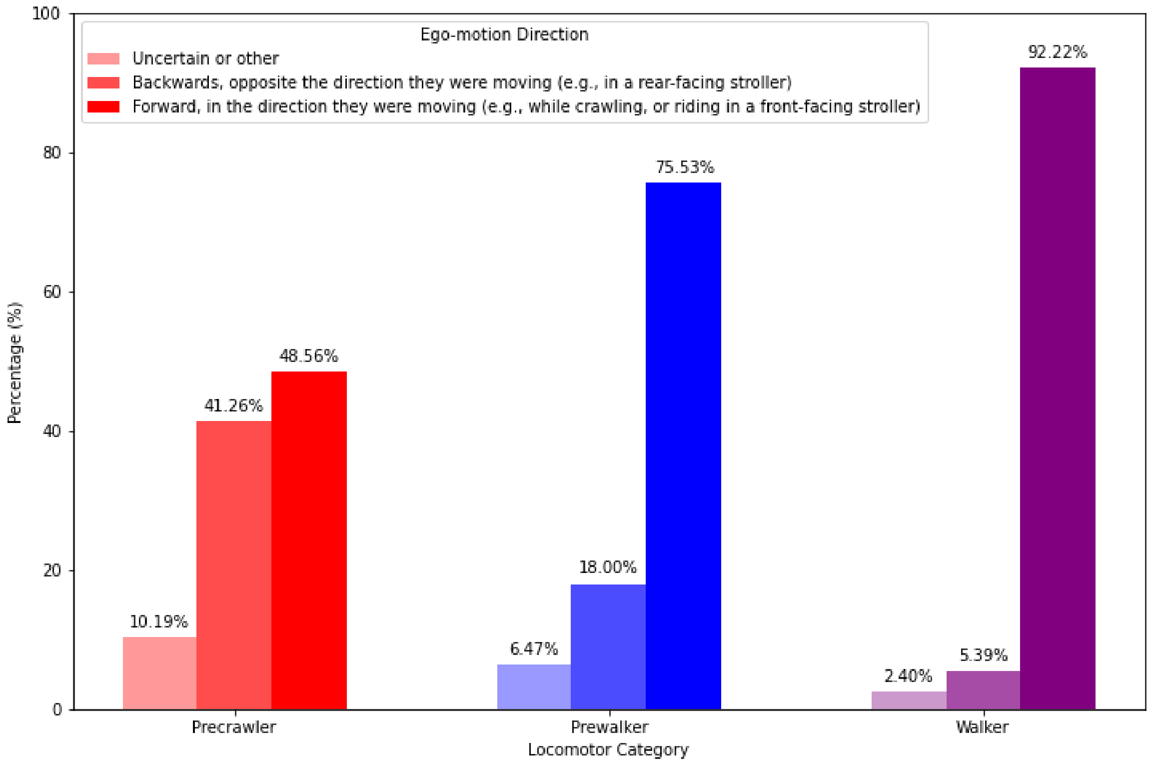

Figure 3.5: Results for overall ego-motion facing direction experience. Overall ego-motion direction experience was assessed based on responses to survey Q2 ("Is the child awake right now"), survey question 3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?") and survey question 7 ("Think of the most recent time you saw the child awake and moving through the environment. Which direction was the child primarily looking while moving?"). We took the subset of responses that were "Yes" for question 2 and question 3, and found the percentage of facing directional motion ("Uncertain or other", "Backward", or "Forward") as a percentage of time of each locomotor group's ego-motion experience. Precrawlers: "Uncertain or other" responses = 60, "Backward" responses = 243, "Forward" responses = 286, total responses = 589. Prewalkers: "Uncertain or other" responses = 55, "Backward" responses = 153, "Forward" responses = 642, total responses = 850. Walkers: "Uncertain or other" responses = 8, "Backward" responses = 18, "Forward" responses = 308, total responses = 334.

Are developmental changes in facing direction during ego-motion explained by age, locomotor status, or both? To address this question, we fit a logistic mixed effects regression model with the expression:

$$\text{lmer}(forward\_motion \sim age + precrawling + (1|subject))$$

This analysis was conducted on the subset of responses in which parents indicated that their child had experienced awake, ego-motion in the last five minutes (i.e., “yes” on both survey Q2 and Q3). The outcome variable $forward\_motion$ was based on survey Q7, with responses coded as 1 for “forward motion” and 0 for “backward motion” (unknown or other responses are ignored). Age values were expressed as days of age at the time of response, and z-scored. The precrawling variable was one-hot encoded (i.e., 1 for “precrawlers”, 0 for “prewalkers” and “walkers”). Prewalkers and walkers were treated as the reference category. We originally considered walking status in addition to precrawling, but found walking status and age to be highly collinear; walking was therefore dropped from the model. This analysis revealed significant change with age ($p<0.001$, $z = 4.60$, 95% CI =[0.40, 1.06]) and significant change with precrawlers ($p<0.001$, $z = -4.00$, 95% CI = [-1.72, -0.57]) (Figure 3.6).

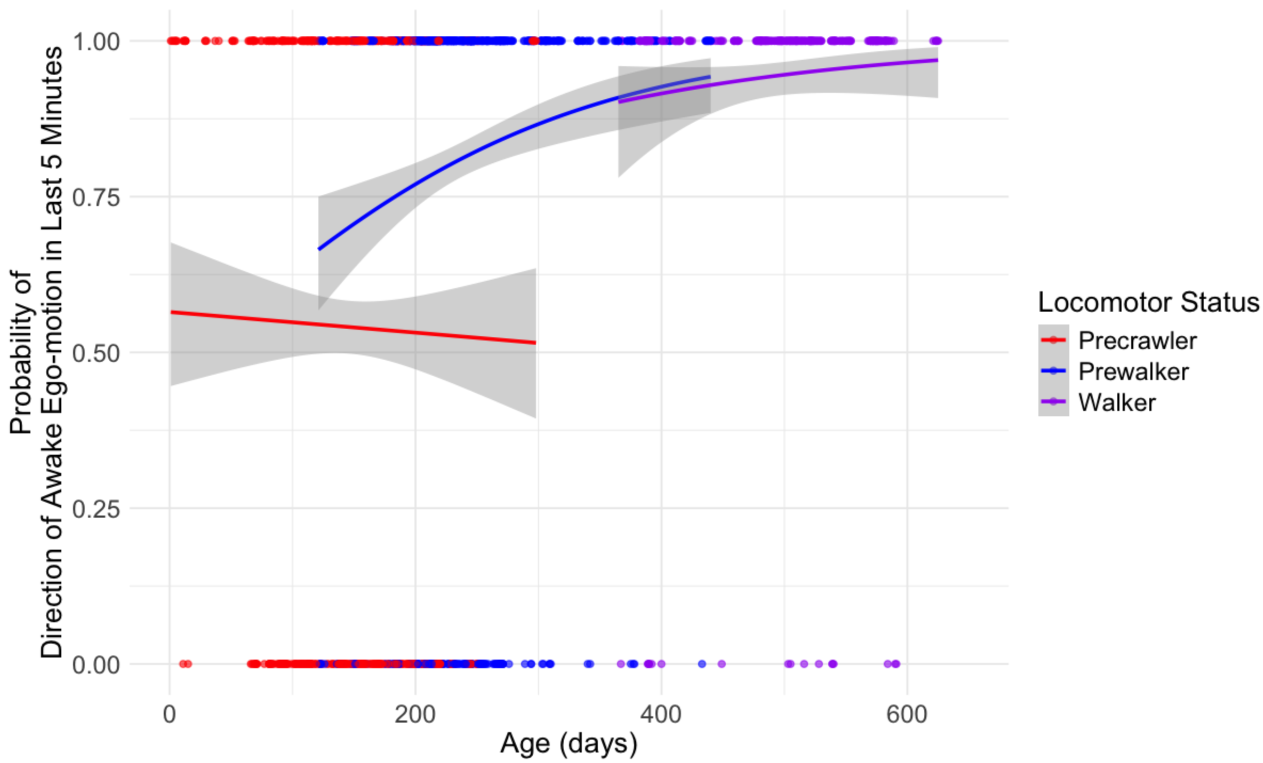

Figure 3.6: Results for age and locomotion-related change in ego-motion facing direction. Overall ego-motion direction experience was assessed based on responses to survey Q2 ("Is your child awake?"), Q3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?"), and Q7 ("Think of the most recent time you saw the child awake and moving through the environment. Which direction was the child primarily looking while moving?"). On the y-axis, values of 1 indicate forward-facing motion, while values of 0 indicate backward-facing motion. Trend lines indicate the probability of forward-facing ego-motion with age, as determined through logistic mixed-model regression, described in the text. Individual responses are indicated by colored markers, where colors correspond to locomotor group membership. Shaded areas indicate 95% confidence intervals.

3.4 Duration of ego-motion experiences

A second possibility is that precrawling ego-motion experience differs in the duration of bouts of ego-motion. To quantify the duration of bouts of ego-motion in precrawling infants, relative to older locomotor groups, we analyzed the subset of survey responses in which parents indicated "Yes" to survey Q2 ("Is your child awake") and Q3 ("Was your child moving in the last 5 minutes?"). For each locomotor group, we used survey Q8 to calculate the proportion of ego-motion responses indicated as “for a few seconds”, “for a few minutes”, or “for ten minutes or more.” The duration of precrawlers experience in awake ego-motion for a few minutes is 24.14% of the time, 40.82% for prewalkers, and 50% for walkers. Both prewalkers and walkers experience longer durations of awake egomotion experience than precrawlers, 61.23% for prewalkers and 82.50% for walkers, compared to precrawlers who experience 37.93% (Figure 3.7).

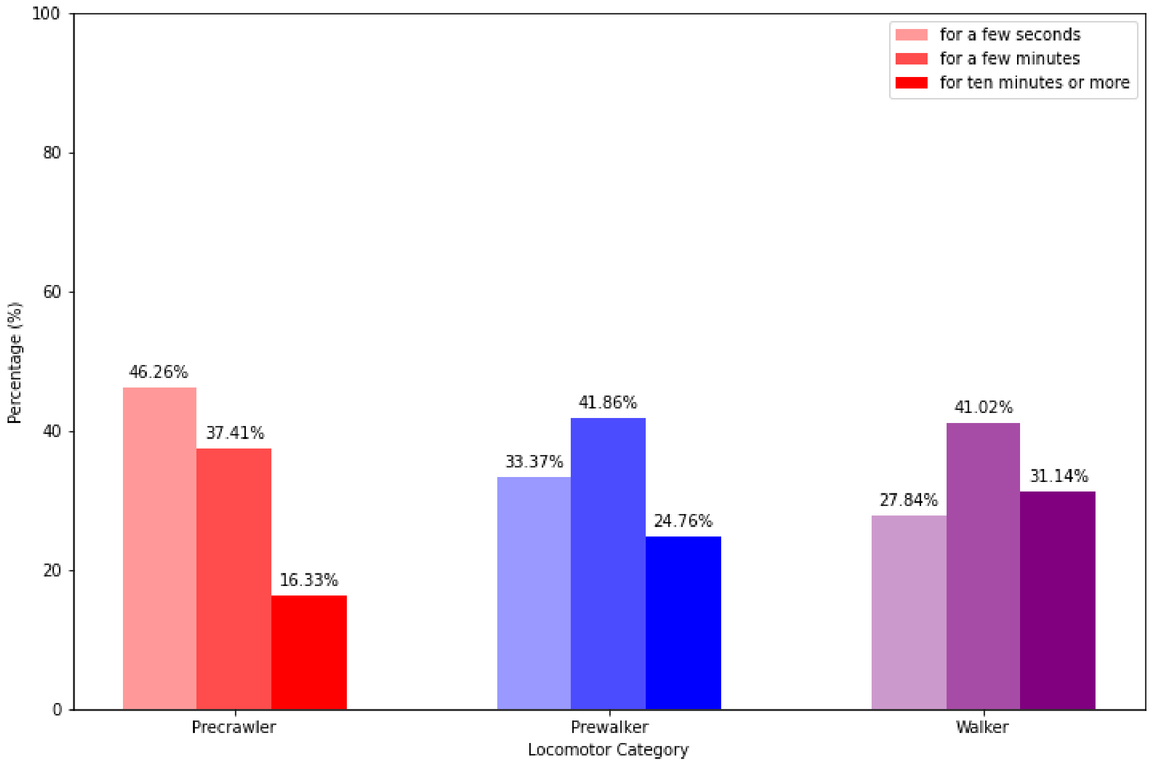

Figure 3.7: Results for duration of ego-motion experience. The duration of ego-motion experience was assessed based on responses to survey Q2 ("Is your child awake?"), Q3 ("In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?"), and Q8 ("Last question! Think of the most recent time you saw the child awake and moving through the environment. How long was the child moving that way?"). We took the subset of responses that were "Yes" for question 2 and question 3, and within each locomotor group, found the composition of the duration of ego-motion experience ("for a few seconds", "for a few minutes", or "for ten minutes or more"). Precrawlers: "For a few seconds" responses = 272, "For a few minutes" responses = 220, "For ten minutes or more" responses = 96, total responses = 588. Prewalkers: "For a few seconds" responses = 283, "For a few minutes" responses = 355, "For ten minutes or more" responses = 210, total responses = 848. Walkers: "For a few seconds" responses = 93, "For a few minutes" responses = 137, "For ten minutes or more" responses = 104, total responses = 334.

To understand the nature of any observed developmental changes, we further fit a logistic mixed effects regression model with the expression:

$$\text{lmer}(duration\_motion \sim age + precrawling + (1|subject))$$

This analysis was conducted on the subset of responses in which parents indicated that their child had experienced awake, ego-motion in the last five minutes (i.e., “Yes” on both survey Q2 and Q3). The outcome variable *duration_egomotion* was based on survey Q8, with responses coded as 1 for both “For a few minutes” and “For ten minutes or more”, and coded as 0 for “For a few seconds”. Age values were expressed as days of age at time of response and z-scored. The precrawling variable was one-hot encoded (i.e., 1 for “precrawlers”, 0 for “prewalkers” and “walkers”). Prewalkers and walkers are treated as the reference category. This analysis revealed no significant change with age ($p = 0.19$) and significant change with precrawlers ($p < 0.05$, $z = -2.53$, 95% CI = [-1.03, -0.075]) (Figure 3.8).

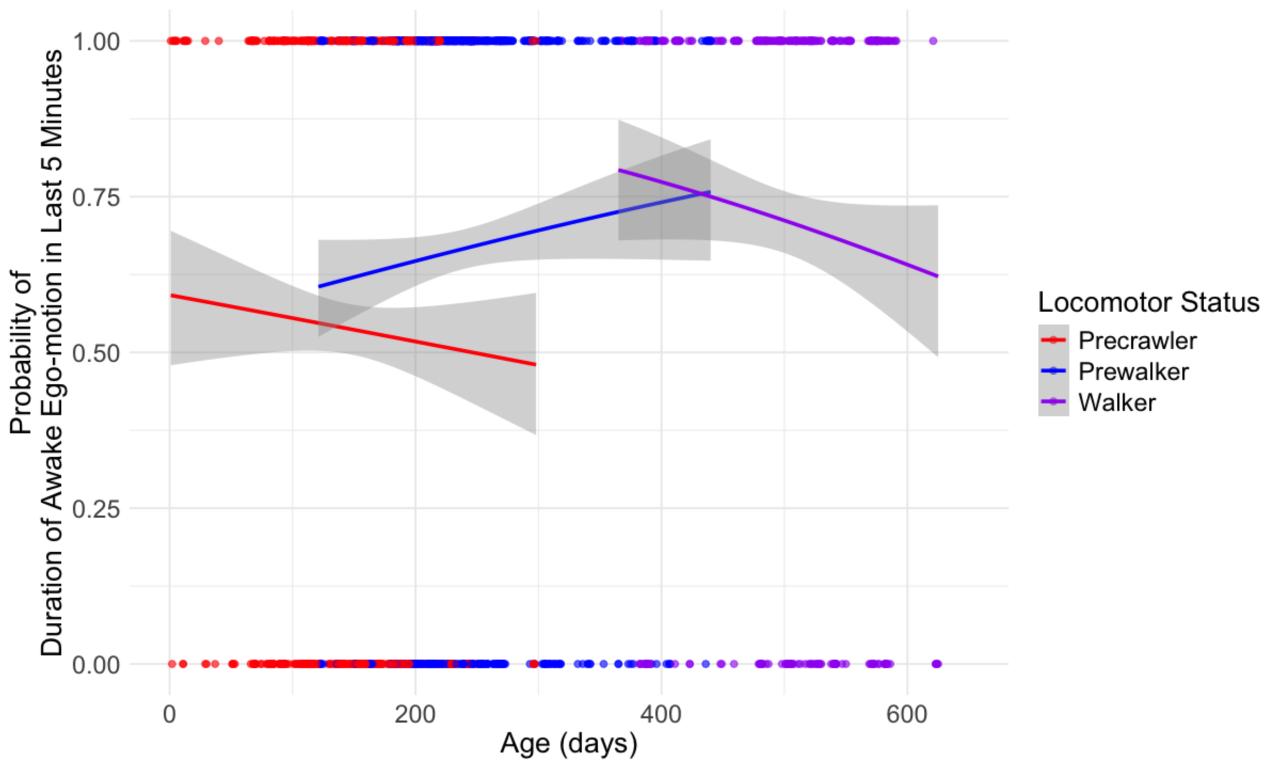

Figure 3.8: Results for age- and locomotion-related change in duration of ego-motion. The duration of ego-motion experience was assessed based on responses to survey Q2 (“Is your child awake?”), Q3 (“In the last five minutes, was the child ever moving through their environment (e.g., by crawling, walking, being carried, or riding in a stroller or car)?”), and Q8 (“Last question! Think of the most recent time you saw the child awake and moving through the environment. How long was the child moving that way?”). We took the subset of responses that were “Yes” for question 3, and coded duration_egomotion as 1 if responses to question 8 were either “for a few minutes” or “for ten minutes or more”, and 0 if the response was “for a few seconds.” The predicted probability of selecting 1 for duration_egomotion, as determined via logistic regression, is shown on the y-axis. Individual responses are indicated by colored markers, where colors correspond to locomotor group membership. Shaded areas indicate 95% confidence intervals.

4 Discussion

The current study investigated infants' and toddler's typical daily experiences with ego-motion through scenes, with a focus on how these experiences change with age and locomotor experience (i.e., learning to crawl and walk). Using EMA, we found several key findings. First, we showed that even prior to the onset of locomotion, infants already gain considerable ego-motion experience, including experience facing forward while moving through scenes - the typical visual experience of visually-guided navigation. Second, we found clear evidence that the onset of locomotion nevertheless increases ego-motion experience, even accounting for effects of age. Third, we found that the nature of ego-motion experiences shifts with age and locomotor status. In particular, passive, pre-crawling ego-motion experience includes almost an even distribution of backwards and forward facing motion, with shorter bouts of ego-motion, but the onset of independent locomotion changes the majority of their experience to be forward facing, with longer bouts of ego-motion.

Precrawling infants first experience the world through passive navigation; their ego-motion is completely controlled by others, often when carried by their parents or moved in strollers. In this way, we found that infants nevertheless receive abundant experience with ego-motion through scenes – the critical visual input for navigation, and thus a proxy for exposure to the visual statistics of scenes. Specifically, we found that parents of infants reported ego-motion in the last 5 minutes for 47.20% of responses. Of these responses, 48.56% were reported to be forward-facing – a greater percentage than any other direction. In short then, 22.92% of pre-crawling infants responses indicated forward-facing, ego-motion through scenes. These data provide critical insight for future theorizing about the role of experience in the development of visually-guided navigation. Clearly, experience with the visual experience of navigation, and thus exposure to critical visual scene statistics, begins long before infants can ever actively navigate themselves.

Despite this early experience in pre-crawlers, our data also indicate that once children are able to actively control their own ego-motion, their navigation experience rapidly shifts in several respects. First, older pre-walking and walking infants and toddlers spend more time awake, leading to an increase in overall ego-motion experience. Second, as soon as they are capable of independent navigation, they begin to use that ability quite routinely; pre-walking infants controlled their own motion on 51.47% of reported ego-motion experiences, and walking infants controlled their own motion on 82.49% of reported ego-motion experiences. Third, although forward-facing ego-motion is already present in the passive ego-motion experience of pre-crawling infants, ego-motion experience shifts to almost completely forward-facing by the time infants are walking. Fourth, the duration of bouts of ego-motion changes over development; precrawler's ego-motion experiences most commonly last just a few seconds, whereas walker's ego-motion experiences typically last for a few minutes or more. We suggest that these changes indicate that crawling and walking experience increase the overall exposure to visual statistics, but do not necessarily induce qualitatively different ego-motion experiences, relative to that experienced passively at pre-crawling ages.

While this research provides novel insight into the quantity and nature of infants' typical ego-motion experiences through scenes, there are several limitations of our approach. First, survey methods are subject to errors in reporting; for example, it is not always possible for parents to be physically with their children at the time of survey; they might not respond to surveys immediately; and they might misunderstand questions, introducing some inaccuracies in reporting (e.g., we found a non-trivial percentage of parents of pre-crawling infants nevertheless indicated that their child was controlling their own ego-motion). Future work replicating these results in new samples, and using multiple measures of navigational experience, will help increase confidence in the conclusions drawn here. Second, our sample did not contain a sufficient number of infants to dissociate effects of age from effects due to learning to walk. In ongoing work, we are recruiting additional infants ages 9 to 14 months – the range during which walking onset typically begins – which will allow us to understand how walking ability relates to ego-motion experience. Third, while EMA survey methods are powerful for gaining a representative sample of ego-motion experience, this approach cannot provide a rich or detailed understanding of the more specific nature of visual scene statistics that infants experience. Our survey questions probed ego-motion through scenes, including forward-facing ego-motion specifically, as a proxy for visual scene statistics. However, to understand the nature of those visual statistics more precisely, and how they change with age and locomotor experience, will require approaches like headcam data that richly capture infants' first-person experiences. This work could also be complemented with additional EMA data asking new, more specific questions about infant and toddler ego-motion experience with scenes. Finally, even after experience is richly characterized, future work will be required to understand the behavioral consequences of this experience. In ongoing work, we are also studying infants' attentional preferences for navigational affordances, and planning to relate this looking behavior to the same infants experiences with ego-motion, as assessed through EMA methods reported here.

In conclusion, we found that precrawling infants gain significant passive exposure to their navigational experience before they begin actively navigating. With age and the onset of locomotion, the quantity of forward-facing ego-motion nevertheless increases. These results set the stage for future work investigating the functional consequences of this typical visual experience in the development of visually-guided navigation behavior.

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