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Spatial Uncertainty and Information Processing Speed in Infants and Adults: Age Differences in Saccadic Reaction Time Sensitivity

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ABSTRACT
Speed of information processing (SIP) as determined by the response to spatial uncertainty is an important, perhaps limiting, factor for cognitive development. With adults, although their manual response to RTs for spatial uncertainty increases linearly with increasing choices, their saccadic RTs do not. In contrast, 7-month-old infants' saccadic RTs have been shown to increase with more target choices. What is the developmental course that enables this saccadic RT discrepancy between 7-month-olds and adults? To address this question, the present study assessed Canadian adults' and 5- and 9-month-old infants' reactive saccades in a comparable choice reaction time task that varied spatial uncertainty. Both 5- and 9-month-olds' saccadic RTs increased linearly with more choice alternatives and uncertainty. Nine-month-olds' saccadic RTs increased at a shallower rate, however, approaching the slope of adults' saccadic RT function, which did not exhibit an increase with more uncertainty. Thus, there is a developmental trend for assessing spatial SIP with saccadic RTs. As infants age, saccadic responses become less sensitive to spatial uncertainty and approach adult-like performance. Decreasing saccade sensitivity may be due to developmental changes in the influence of response selection or in the functioning of inhibitory mechanisms.

Introduction

The assessment of the speed of information processing (SIP) has been a prominent issue throughout the history of psychology. This is due in part to many researchers theorizing that SIP reflects the efficiency at which humans attend, process, and respond to information (e.g., Donders, 1969; Jensen, 1987, 1993, 1998; Jensen & Munro, 1979; Kraft & Woods, 2021; Salthouse, 1985). The benefit of efficient information processing is evident in adults as those who have faster SIP score higher on measures of intelligence (Coyle, 2022; Jensen, 1987, 1998; R. Kail, 2000; Sheppard & Vernon, 2008). Because of the apparent relation between SIP and intelligence, researchers have sought to understand how SIP develops and mediates higher cognitive abilities across the lifespan (Fry & Hale, 2000, 1996; R. V. Kail et al., 2016; Shen & Wei, 2023; Vanhala et al., 2023), as well as the relation of SIP to the underlying neural structure (Li et al., 2023). Thus, SIP development may be an important limiting factor for cognitive development.

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SIP framework

The primary framework for studying SIP in adults has been based on Hick's law (Hick, 1952) in which information is defined in terms of the inputs that reduce the uncertainty in selecting and initiating a response (Hick, 1952). Responding is then related to uncertainty by the function that has become known as Hick's law – as uncertainty increases (by increases in the bits of information), reaction time (RT) increases in a log-linear fashion. With a bit (a contraction of binary digits) of information being mathematically described as the logarithm to the base 2 ($\log_2$) of the number of possible choices (Jensen, 1993), Hick's law is then expressed as: $RT = a + b \log_2 n$, where a is the intercept, n is the number of choices, and b is the slope of the regression of RT on $\log_2 n$ (Jensen, 1987).

In classic SIP tasks (Jensen, 1998; Jensen & Munro, 1979; Vernon, 1983), the participant views a display consisting of a set of lights with one, two, four, six, or eight potential targets (or bits of information) that can light up individually (for a review see Jensen, 1987). In any given target condition only one light will randomly light up during a trial creating a spatial uncertainty for the target's appearance. The participant depresses a central home button until one of the possible target lights randomly illuminates, after which the participant takes his or her finger off the home button and moves it to the button that corresponds to the lit target. The time it takes to release the home button serves as the RT and has been shown to be affected by SIP, increasing with more spatial uncertainty due to more potential choices (Jensen, 1987). Consistent with this general SIP phenomenon, more recent research has similarly demonstrated that even in a cueing paradigm, increasing the number of locations that are cued, which increases spatial uncertainty, produced a concordant increase in RT to the subsequent target (Huang, Xue, Wang, & Chen, 2016).

SIP and early development

To gain insight into the nature of SIP during early development, initial infant studies sought to measure SIP by means of habituation (see Bornstein & Sigman, 1986). Though these studies have related infants' SIP to later developments, such as its relation to children's IQ (Rose & Feldman, 1997) and general cognitive capacity (Rose, et al., 2008), infants' SIP in response to spatial uncertainty relative to adults' has not received much focus. This occurs despite the mechanisms underlying adults' processing presumably begin their developmental journey in infancy. Though habituation may be viable for content discrimination tasks (when infants dishabituate to a new stimulus), using it as a measure of SIP involving spatial uncertainty, however, is likely problematic.

That is because, as outlined, in many SIP studies with adults, the task requires participants to make a spatial choice from among differing numbers of simultaneously possible alternatives (e.g., Huang et al., 2016; Jensen, 1998). Infant habituation studies lack this component of the SIP task and thus are missing the capacity to measure sensitivity to changes in spatial uncertainty as an assessment of SIP (e.g., Der & Deary, 2006; Jensen, 2005). Habituation studies, though, likely do assess the speed with which the content of events is processed once they have been spatially chosen from amidst the uncertainty of other spatially available stimulus events. Another major difference, as pointed out by Dougherty and Haith (2002), between infant habituation and typical adult studies, is that SIP with a habituation paradigm is assessed on a scale of seconds, whereas in the adult literature, SIP is measured in milliseconds with reaction time tasks. Finally, as adult SIP is measured with an analogous continuous rate variable (i.e., RT), looking paradigms' use of percentage of fixation time is not comparable. Similar issues have been raised and addressed in studying other target selection processes in development (see Adler, 2005; Adler & Orprecio, 2006; Baker et al., 2008; Comishen & Adler, 2019). As a consequence, habituation studies are likely not best positioned to determine the nature of SIP development in making a choice under conditions of uncertainty when there are spatially available alternatives.

To overcome these issues, some subsequent SIP studies used infants' saccadic latencies to spatially predictable target sequences of events (Dougherty & Haith, 1997; Rose et al., 2004; Rose, Feldman, & Jankowski, 2002). Infants' eye movements have the advantage of being assessed on the order of milliseconds along a continuous scale, comparable to the RT measurement scale in adult studies (e.g., Adler, 2005; Adler & Gallego, 2014; Adler & Orprecio, 2006), thereby allowing for a more direct developmental comparison. In these SIP-infant eye movement studies, as infants learn a spatial sequence of stimulus events, they begin to initiate saccades with faster latencies or RTs (Haith et al., 1988; Rose, Feldman, Jankowski, & Caro, 2002), possibly indexing an aspect of SIP, as well as working memory and attention.

Though the infant eye movement paradigm solved the timing and comparison problems of assessing infants' SIP in habituation studies, the lack of infants having to make a choice under random levels of spatial uncertainty (due to the predictable spatial certainty found in the infant eye movement paradigm) as is typical in adult SIP studies remained (Dougherty & Haith, 2002). To solve this issue, Dougherty and Haith (2002) measured infants' saccadic RTs in a choice reaction task comparable to that used with adults. Recording infants' RTs when making a spatial choice as the measure of underlying processing speed as done in adult research (see Smith, 1968 for a review) was therefore thought by Dougherty and Haith (2002) to represent a more comparable method for assessing the development of SIP in infancy.

In their study, Dougherty and Haith (2002) randomly presented 7-month-old infants with varied number of possible visual target locations (1, 2, or 4). Results revealed a positive function of infants' RT to initiate a saccade to a spatial target with increasing number of possible target locations. Although these findings are strikingly similar to those found with manual RTs in adults, the between-participants design used may have enabled infants in the 1-location group to learn a perfectly predictable sequence (100% predictability), whereas the other target groups had less predictability (2-location group: 50% predictability; 4-location: 25% predictability), thereby producing faster saccades for the 1-location group (e.g., Haith et al., 1988). To account for this possibility and verify if infants' reactive saccades are consistent in a paradigm more similar to that used with adults, the present study used a within-participants design. In addition, in order to be more consistent with the number of possible targets used in adult studies, the present study assessed infants' saccades with more possible targets (up to 8 potential targets).

That infant saccadic RTs may increase with more possible choices is theoretically interesting from a developmental perspective. One reason is that in this framework *information* is defined as the reduction of spatial uncertainty (Hick, 1952); hence, highly predictable events convey little information because they require less processing resources, yet less predictable or more uncertain events convey greater information because they require more processing resources in order to make a decision, in line with the levels-of-processing theory of cognition (Craik & Lockhart, 1972). As a consequence, SIP slows when more resources are needed to make a decision in situations where choice increases in uncertainty. Developmentally, for infants who have more limited processing resources, the impact of uncertainty and SIP may become more consequential. The increase in saccadic RTs as uncertainty increased in 7-month-olds (Dougherty & Haith, 2002) would seem to suggest that SIP is being indexed (Jensen, 2005) in the infants and, consequently, measuring infants' saccades represents a viable means for assessing SIP in early development. Adults' saccadic sensitivity to spatial uncertainty as a measure of SIP, in contrast, has been found to be low in some studies as evidenced by relatively flat and even negative saccadic RT functions relative to the number of bits of information, although at the same time their manual sensitivity is generally high (Kveraga & Hughes, 2005; Kveraga et al., 2002; Lawrence et al., 2008). Whether the sensitivity difference reflects a dissociation in processing speed influences on these distinct behavioral responses, reaching versus eye movements (see Dougherty & Haith, 1997), or is due to different developmental statuses is unknown. Consequently, what underlies this dichotomy between manual reaching versus saccades in sensitivity to spatial uncertainty, is unclear. That infants exhibit a positive function opens up the possibility that exploring the development of SIP of spatially determined stimuli as measured by saccadic RTs might inform about the responsible mechanism.

Purpose

In the present study, the development of SIP for spatially defined items was measured by examining both infants' and adults' responses to uncertainty in a paradigm that is more comparable to those previously used with adults. To this end, both manual and saccadic RT responses in adults and saccadic RT responses in infants were recorded as they performed a choice reaction task (e.g., Dougherty & Haith, 2002). Placing both adults' and infants' performance in the same SIP theoretical and empirical context and enlarging the infant age range around 7 months, a window could potentially be opened into reasons, mechanistic and developmental, that might account for the discrepancy in saccadic sensitivity to spatial uncertainty as a measure of SIP in infants and adults and advance our understanding of SIP for spatially defined items from early development to adulthood.

Experiment 1: adult manual and saccadic RTs

The purpose of the first experiment was to obtain a baseline assessment of adults' SIP in the current paradigm with both manual and saccadic responses and to confirm similar results with those reported previously (Gignac & Vernon, 2004; Jensen, 1987; Lawrence et al., 2008). That is, the current paradigm is expected to reveal, as previous studies have, that adults' manual RTs increase with increasing spatial uncertainty (Gignac & Vernon, 2004; Jensen, 1987), whereas their saccadic RTs in contrast remain relatively flat with increasing uncertainty (e.g., Kveraga & Hughes, 2005; Kveraga et al., 2002; Lawrence et al., 2008).

Method

Participants

Ten Canadian adults (*M* age = 22 years, *SD* = 1.78, range: 19–24 years; 2 males, 8 females), recruited from the University Research Pool and offered partial course credit, participated in this experiment. Approval from the York University Ethics Review Board was obtained for this study prior to its commencement. All participants were asked to fill out a consent form and a brief demographic questionnaire sheet prior to their participation. Participants were Caucasian (*n* = 7), Hispanic (*n* = 2), and Asian (*n* = 1) and were from a middle socio-economic status (SES) background. Participants had normal or corrected to normal vision. On the basis of previous eye movement studies that used ANOVAs and regressions, for both adults and infants, to obtain power (1 – ß) equal to .90 with a standard deviation of 1.0, a minimum of 9 participants per experiment was required.

Stimuli and apparatus

The stimuli consisted of computer-generated graphic images displayed on a 19-inch monitor with 1024 × 768 pixel resolution, a refresh rate of 60 hz, and an 8 bit/pixel grayscale. The stimuli were arranged in a circular grid that had a radius of 6° of visual angle from a central fixation stimulus on a gray background (see Figure 1(a)). The central fixation stimulus was a red colored box which subtended a visual angle of 2° and the target stimuli (a cartoon baby face) each subtended a visual angle of 3.5°. The target could appear in 1, 2, 4, 6, or 8 possible locations, corresponding to 0, 1, 2, 2.58, or 3 bits of information, respectively. On each trial, the number of potential target locations was made salient with 4° square boxes or *spatial frames*, similar to how potential target lights were visible (whether lit or not) to participants in Jensen's studies (Jensen, 1987; Jensen & Munro, 1979). The locations of the spatial frames were randomized across trials and the different possible choice conditions.

Eye movements were recorded with a remote, infrared eye-tracker (Model 504, Applied Sciences Laboratories, Bedford, MA, USA) using bright pupil technology at a temporal resolution of 60 hz. Infrared light emitted from diodes on the camera reflected back from the participant's retina through the pupil producing a backlit white pupil. In addition, the infrared light produced a point reflection (the first Purkinje image) on the corneal surface of the eye. The relation between the corneal reflection and the centroid of the backlit pupil was used to calculate via proprietary algorithms (Applied Sciences Laboratories), the fixation locations, changes in locations of the eye over time, and consequently the eye movements themselves.

An IBM computer running Presentation software (Version 9.2, www.neuro-bs.com) was used to generate and present the stimuli to participants. A Dell computer ran Applied Science Laboratories 6000 series proprietary software for the collection of eye movement data. The Presentation software was programmed to send a time-stamped numeric value over the stimuli-generating computer's parallel port at the onset of each new stimulus to the data-collecting computer to enable synchronization of trial onset (and type of trial) with the collected eye movement data. Manual responses were recorded with a QWERTY keyboard number pad. The number pad was mapped directly to the stimulus presentation location on the monitor, where the number 5 button served as the "home" button and the numbers 1, 2, 3, 4, 6, 7, 8, and 9 served as the response buttons that corresponded to the potential target locations (and similar to the

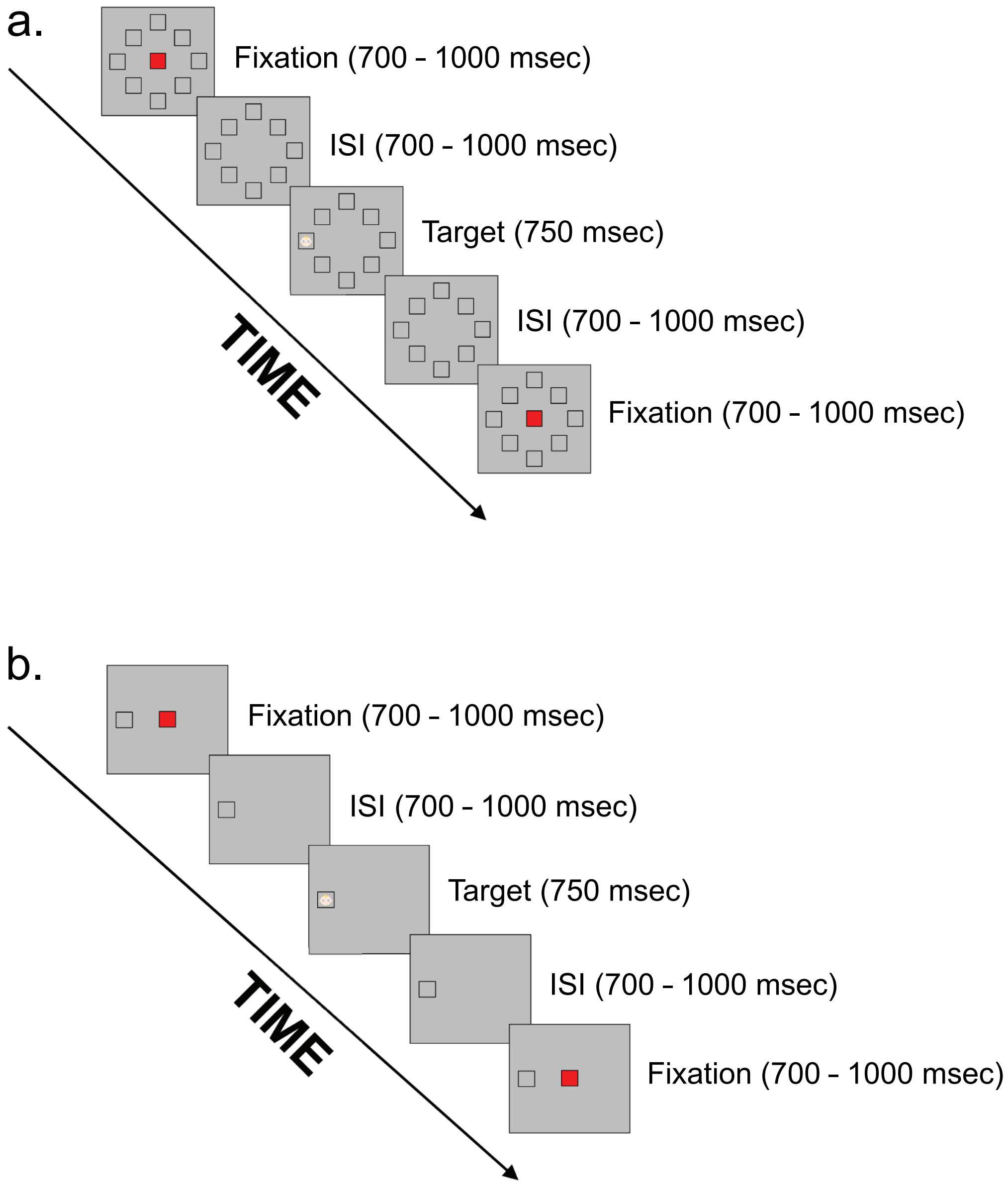

Figure 1. (a) Sample trial sequence of events for the visual display with 8 potential target location (3 bits) condition. (b) Sample trial sequence of events for the visual display with 1 potential target location (0 bits) condition. The number of spatial frames varied with the number of bits of information.

directions their eyes needed to move with saccadic responses). Responses were synced with the presentation stimulus via Presentation software and recorded in a log file for offline analysis.

Procedure

Adults were seated at a distance of 48 cm from the stimulus monitor with the eye-tracker camera situated beneath the monitor and the response keyboard placed in front of them.

Eye movements and manual responses were recorded in two separate sets of trial blocks, with which response type occurred in the first block counterbalanced across participants.

Participants viewed the five potential target location conditions across five blocks of 20 trials each, with the blocks presented in random order to reduce practice effects (see Carroll, 1987; Longstreth, 1984). On an individual trial for both the manual and saccadic tasks, the fixation square and spatial frames were presented for 700 to 1,000 msec, randomly varying by increments of 33 msec from trial-to-trial. This was followed by an ISI that randomly varied between 700 and 1,000 msec by increments of 33 msec, during which the empty target spatial frames remained. The target (a cartoon baby face) was then presented in one of up to eight possible locations (depending on the condition) for 750 msec, followed by a variable ISI of between 700 and 1,000 msec in increments of 33 msec (see Figure 1). Varied timing was used throughout the trials in order to minimize the learning of a predictable timing sequence that could support the formation of expectations and be used to anticipate the events (e.g., Adler et al., 2008; Comishen & Adler, 2019), thereby biasing the assessment of the speed of information processing.

The presentation of the targets was further randomized with the constraint that targets appeared in all possible target locations on the equivalent number of trials in each target condition. For example, in the 2-target condition, the presentation of the target on 10 trials occurred in one target location and on 10 trials in the other target location, whereas in the 4-target condition, targets appeared for 5 trials in each target location. For 6- and 8-target conditions, out of 20 possible trials, each location contained a target on at least 3 (6-target condition) or 2 (8-target condition) trials, with the remaining trials randomly assigned to any of the locations with the criterion that across participants each location was counterbalanced as equally likely to contain a target.

During the manual response task, participants were instructed to use the index finger of their dominant hand. Five practice trials were given on the 8-targets condition (3 bits of information) to familiarize participants with the mapping of the location of the potential targets to the keypad buttons. Participants were instructed to keep the 5 or “home” button depressed when the red fixation stimulus was on and during the ISI. They were further instructed to release the home button only when one of the targets appeared. The time it took to release the home button after target onset served as the measure of manual RT.

The saccadic response task used the exact same stimuli and procedure as the manual response task with the exception being that the keyboard was removed. Once the participant was seated comfortably, and the eye-tracker was properly positioned and focused, eye calibration began. The eye-tracker was calibrated by having adults fixate sequentially on nine circles (three rows of three) presented at known locations on a computer monitor. All subsequent eye data were filtered through these calibration values. Once the calibration was completed, adults were instructed that they would see computer images with up to 8 possible target locations (indicated by empty boxes where the target could appear, see Figure 1), as well as the central fixation square. Participants were instructed to remain fixated on the fixation square until a target appeared. Once the target appeared, the participants were instructed to make an eye movement to the target and then back to the stimulus fixation square location. The time to initiate the eye movement (i.e., saccade latency) to the target served as a measure of saccadic RT. Eye movement initiation was operationalized as equivalent to manually releasing the home button, thereby paralleling manual and saccadic RTs.

Data reduction and analysis

Manual responses. Active responses were recorded, including the RT to release the home button, and stored in a log file for offline analysis. To be consistent with the eye movement measurement criteria (indicated below), any RT to release the home button that occurred less than 100 msec after target onset were considered anticipatory and were also excluded from the analysis. The means of the median manual RTs were used for further analysis.

Eye movements. The raw eye movement digital data were imported into a MATLAB toolbox called ILAB (Gitelman, 2002) for subsequent analysis. The ILAB toolbox software allows analysis of eye movements, separating out and displaying individually the horizontal and vertical components of the eye movement, on a trial-by-trial basis. Moreover, ILAB provides a means by which to display the scan path of the eye on a trial-by-trial basis and thereby determine whether or not the eye first fixated on the central fixation stimulus and the parameters of the eye movement (direction, distance, RT, etc.) relative to the location of the target. In order for an eye movement to be included in the final RT data pool, it had to meet a number of criteria. First, the participants were required to be fixating the fixation stimulus before the onset of the target stimulus and could not initiate an anticipatory eye movement to any of the possible locations during the ISI. Second, only when adults' first eye movement was toward the target after the target stimulus appeared was the RT (latency) measured. Third, an eye movement that began before 100 msec after target onset was excluded from further analysis as it was considered to be anticipatory (Heeman et al., 2017; Kingstone & Klein, 1993) and not reactive to the target onset and thereby not influenced by SIP. Similarly, any eye movement that was initiated more than 100 msec after target offset was excluded as it was not considered to be reactive to target onset. Finally, eye movements had to fall within a 1° window around the target to be considered valid. Means of the median saccadic RTs were used for further analysis. A minimum of 65% of all trials per participant needed to fit these criteria in order for that participant's data to be included in the final sample.

Results and discussion

Prior SIP studies have settled on regression analyses as the appropriate statistic for examining the relation between RT and the number of bits of information, for both saccadic and manual responses (e.g., Jensen, 1987; Vickrey & Neuringer, 2000). A linear regression analysis was therefore performed for manual responses for which the independent variable was the number of bits of information and the dependent variable was RT. The regression model revealed a significant relation, $r^2 = 0.38$, $F(1, 48) = 29.76$, $p < 0.001$, Cohen's $F^2 = 0.62$, indicating that manual RTs increased as the number of bits of information increased. A positive slope of 46.86 msec per bit was found, further indication that manual RT increased with more bits of information (see Figure 2(a)). These r^2 and slope values are consistent with results from other SIP task studies (e.g., Jensen, 1987; Neubauer, 1991).

A linear regression analysis performed on adult saccadic eye movements, in contrast, was not significant, $r^2 = 0.005$, $F(1,\ 48) = 0.284$, $p = 0.60$, *ns*, indicating that RT did not increase as the bits of information increased. The slope of the regression line was found to be −3.41 msec per bit, confirming a flat saccadic RT by the number of bits function (see Figure 2(b)). Comparing the manual RT versus

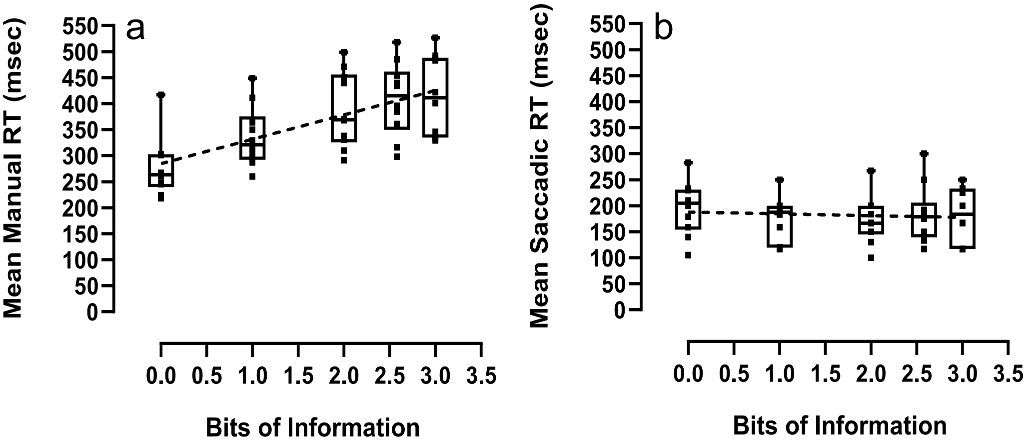

Figure 2. (a) Box plots and regression analysis for adults' manual RTs plotted as a function of bits of information. Dashed line: RT = 284.77 + 46.86 $\log_2 n$, $p < 0.001$ (b) Box plots and regression analysis for adults' saccadic RTs plotted as a function of bits of information. Dashed line: RT = 187.77–3.41 $\log_2 n$, $p = 0.60$, ns.

saccadic RT slopes revealed that they were significantly different, $t(96) = -4.692$, $p < 0.001$, Cohen's $d = 0.96$, indicating that the two response sets were differentially sensitive to increasing spatial uncertainty. The lack of an increasing function for saccadic RTs and instead a slightly decreasing function is also consistent with findings from previous studies with adults (Kveraga & Hughes, 2005; Kveraga et al., 2002; Lawrence et al., 2008).

The results from this experiment are consistent with previous adult SIP studies with manual (e.g., Jensen, 1987; Sheppard & Vernon, 2008) and the saccadic (Kveraga & Hughes, 2005; Kveraga et al., 2002; Lawrence et al., 2008) tasks. Because the same stimulus paradigm was used, methodological explanations could not account for replicating the differences in adult manual RTs and saccadic RTs. That adults' manual and saccadic RTs differ in their sensitivity to increasing spatial uncertainty may reflect a dichotomy in the influence of the speed of information on these distinct behavioral responses, hand versus eye movements (Dougherty & Haith, 1997), and their underlying neural pathways. Furthermore, perhaps the increase in RT with uncertainty for manual responses but not eye movements could be attributed to the additional process of mapping the motor button response which is not required for saccades. Prior research, however, in which a considerable amount of trials was provided to instantiate the motor mapping showed that the effect of the number of choices on RT was not diminished (Hale, 1968; Teichner & Krebs, 1974), suggesting that the additional motor mapping process for manual responses cannot account for RT sensitivity differences between response types.

Alternatively, in adults, this dissociation in sensitivity may echo differential developmental impacts of the speed of information processing on these response systems, as some infant studies have found an effect of increasing spatial uncertainty on saccadic RT (e.g., Dougherty & Haith, 1997). In other words, perhaps eye movements are influenced earlier in development by speed of information effects than mature eye movement systems. To help illuminate whether there is a differential development in the sensitivity of the saccadic system to increasing choices and spatial uncertainty, infants' saccadic RTs were assessed using the same saccadic task as in Experiment 1.

Experiment 2 - infant saccadic RTs

Previous developmental research has indicated that as infants age, they become faster at tasks that require speeded responses in the presence of some uncertainty (Rose, Feldman, & Jankowski, 2002; Rose, Feldman, Jankowski, & Caro, 2002). Additionally, as infants age, the latencies of their reactive saccades to a single target onset for which there was no uncertainty were found to decrease and become adult-like between 6 and 9 months (Canfield et al., 1997). Such findings suggest that there might be a developmental trend in the sensitivity of infants' saccades as a manifestation of the effects of SIP to increasing spatial uncertainty. That is, as infants' neural systems mature, their initiation of saccades to a spatial location in a speeded task, such as a SIP task, might become faster, less sensitive to uncertainty, and the slopes shallower. To date, the only age at which SIP for spatially defined items has been assessed with saccades in a speeded choice task has been 7 months (Dougherty & Haith, 2002), so the developmental course for eye movement sensitivity in infancy has yet to be determined. The purpose of the current experiment, therefore, was to assess the impact of spatial uncertainty with the same task as used with adults in Experiment 1 with two groups of infants that flank in age the Dougherty and Haith (2002) age group, 2 months younger and older, as a means to draw a more complete picture of the developmental trend in infants.

If an increase in infants' saccadic RTs as a function of an increase in spatial uncertainty is found, however, this might reflect an increasing load on limited attentional resources (Braddick & Atkinson, 2011; Colombo, 2001; Reynolds & Romano, 2016) rather than differential saccadic sensitivity to uncertainty as a measure of SIP. In SIP studies (e.g., Jensen, 1987), the number and location of possible targets w2016ere always made salient (just as was presently done with spatial frames in Experiment 1) for each bit condition. This was achieved by allowing the participants to see how many lights were present for each condition. In the Dougherty and Haith (2002) study, however, there were no visual markers for where and how many possible targets might appear, which might have potentially taxed infants' limited attentional resources. To address the potential attentional issue in this experiment, spatial frames, which denote the number and location of potential targets before target onset thereby making them more salient, were present, as they were for adults in Experiment 1. If an increase in infants' saccadic RTs is due to their developmentally limited attentional resources, then providing spatial frames might mitigate that limitation and thereby facilitate SIP and the initiation of infants' eye movements. Consequently, we would expect to see no increase in infants' saccadic RTs as the number of bits of information increases (i.e., consistent with what adults exhibit) and likely no differences as a function of age. If the attentional load is not a factor in infants' saccadic RTs, then any increase as a function of bits or differences as a function of age is likely due to developmental differences in the effect of spatial uncertainty on SIP and saccades.

Experiment 2: 5- and 9-month-old infants

Method

Participants. Twenty Canadian infants, 10 5-month-old (7 males, 3 females) ranging in age from 19 to 24 weeks of age (*M* = 22.05, *SD* = 1.74) and 10 9-month-olds (4 males, 6 females) ranging in age from 33 to 41 weeks of age ($M = 38.5$, $SD = 3.04$), were recruited from a mailing list supplied by a Toronto-area marketing company (Z Retail Marketing Company Inc., Toronto, Canada), and came from primarily middle SES backgrounds, participated in this study. Infants were Caucasian ($n = 13$), Asian ($n = 5$), Hispanic ($n = 1$), and Other ($n = 1$). Infants in this experiment were tested until we had 10 infants at each age who met all of the inclusion criteria (listed below). An additional 17 infants across both ages who participated were excluded from the study because of crying ($n = 5$), inattentiveness or off-task (attending to the stimuli less than 65% of the time, $n = 6$), fussiness (e.g., too much head movement, $n = 5$), and equipment or experimenter error (e.g., poor eye-tracker calibration, $n = 1$). This level of exclusion is consistent with the rates in previous infant eye movement studies (e.g., Adler et al., 2020; Adler & Gallego, 2014; Comishen & Adler, 2019). All infants were born at full-term, in good health, and with no reported visual or neurological abnormalities. Informed consent was given by a parent of each infant.

Stimuli and apparatus. The same eye-tracker, computer setup, software, and stimuli used in Experiment 1 with adults were used in Experiment 2 with the infants. In this experiment, however, saccadic RTs were the only dependent variable. Five- and 9-month-old infants ($n = 20$) participated in an experimental condition defined by the stimulus sequence being presented with spatial frames indicating where the potential targets could appear (as in Experiment 1, see Figure 1). As in Experiment 1, within-participant stimulus conditions included 0, 1, 2, 2.58, and 3 bits of information (1, 2, 4, 6, and 8 possible target locations, respectively). Each bit of information condition was presented in a block of 20 trials, and the order of the blocks was randomized as to avoid order effects (Longstreth, 1984).

The infants viewed the stimuli on a 19-inch LCD color monitor with 1024 × 768 pixel resolution that was mounted 48 centimeters from their eyes. There was a 30 × 30 centimeter infrared-reflecting, visible-transmitting mirror between the infant and monitor. The remote, pan-tilt infrared eye-tracking camera emitted infrared light that was reflected off the mirror and into the infant's eye. The reflection of the infrared light coming back from the infant, through the pupil, and off the mirror was recorded by the camera at a temporal resolution of 60 hz.

Procedure. As with adults, a calibration procedure was first conducted that matched eye coordinates to screen coordinates and through which eye data was filtered. To maintain the infants' attention during focusing of the eye-tracker prior to calibration, a stimulus was presented in the form of a magenta and white oval that moved in a circular pattern. Once the eye-tracker was focused and the positioning of the infant was complete, eye calibration began by having each infant view a continuous loop of varying shapes and colors at two known locations on the screen. All subsequent eye-tracker fixation values were filtered through the calibration file to produce measures of eye position data. The sequence of stimuli and timings in a trial were the same as in Experiment 1.

The only procedural difference between 5- and 9-month-olds was in how they viewed the stimulus sequence. Five-month-old infants were laid supine in a specialized crib and viewed the stimuli on a monitor situated overhead (see Figure 3). To minimize outside light entry and distraction inside the crib, black felt curtains were drawn over and around the crib. Nine-month-olds, however, due to developmental advances such as sitting up, rolling over, and reaching and grasping testing and crib components,

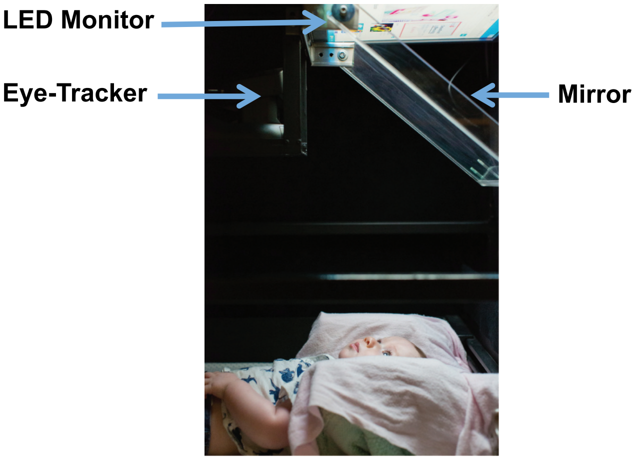

Figure 3. Experimental crib where 5-month-old infants were tested. Infants lay supine with the stimulus monitor mounted above.

establish limits on testing them lying supine in a crib. Instead, 9-month-old infants viewed the stimuli on a monitor situated in front of them while sitting on their caregiver's lap. Though infants' eye movements were measured when in different postures at different ages, there is no evidence in the eye movement literature that posture impacts saccade initiation; in fact, the literature explicitly suggests otherwise (Stamenkovic et al., 2018). Thus, posture was not considered as a factor in comparing infants' performance.

Data reduction. Eye movement data were collected and analyzed as in Experiment 1. Due to the nature of the development of eye movements (e.g., Canfield et al., 1997; Pueyo et al., 2022), some criteria for the inclusion of an eye movement in the final data set were different from those used for adults. First, since the RT to initiate a saccade toward a target was being assessed and to exclude off-task responses that could theoretically increase the median latency measure, the infants, like adults, were required to be fixating on the fixation stimulus immediately prior to the onset of target stimulus presentation and only the latency when infants' first eye movement was in the direction of a target after its onset was measured. Second, in order to only include reactive eye movements and exclude anticipatory eye movements in the final data set, a latency cutoff of 133 msec was used to differentiate a reactive eye movement from an anticipatory eye movement. This latency value was chosen as it has been previously determined that infants around this age cannot make eye movements faster than 133 msec in reaction to target onset (Canfield et al., 1997). Similarly, eye movements that were initiated more than 133 msec after the target offset were excluded, as these were likely in reaction to the offset and not to the onset of the target. Third, the eye movement to the target stimulus had to trace a path that was more than 50% of the distance from the central fixation stimulus to the target. The 50% criterion has been used in previous studies assessing infants' eye movements (e.g., Adler & Haith, 2003; Baker et al., 2008; Comishen & Adler, 2019) and is typically taken as an indication that the eye movement was intentional and not random.

Results and discussion

Preliminary analyses. Because past research has suggested that the efficiency of infants' vertical eye movements develops slower than horizontal eye movements (Grönqvist et al., 2006; Shea, 1992), a preliminary analysis was therefore conducted to assess mean differences in infants' saccadic RTs as a function of possible target location (left, right, upper left, upper right, lower left, lower right, up and down). As the only condition that included all possible target locations was the 3-bit (8 possible targets) condition, an ANOVA was performed by means of the median saccadic RTs[1] in the 3-bit condition as a function of age and location. These analyses revealed no significant differences in the saccadic RT as a function of target location or age nor the interaction of location and age (all p's > 0.2). Thus, there was no cost to saccadic RT due to the target location.

Regression analyses. To determine whether there was a developmental difference in the sensitivity to spatial uncertainty, a multiple linear regression analysis was performed to compare saccadic RT to bits of information (0, 1, 2, 2.58, and 3) as a within-participant variable with age as a between-participant moderator (5-month-olds and 9-month-olds). This analysis found that the main effects of age, $F(1, 90) = 40.77$, $p < 0.001$, $\eta_p{}^2 = 0.31$, and number of bits, $F(4, 90) = 29.95$, $p < 0.001$, $\eta_p{}^2 = 0.57$, were both significant, indicating that saccadic RTs differed across the ages and across the number of bits. The interaction of age and number of bits, as a measure of slope, was also significant, $F(4, 90) = 9.23$, $p < 0.001$, $\eta_p{}^2 = 0.29$, indicating that saccadic RTs increased at different rates with increasing number of bits as a function of age. Post-hoc comparison of the slopes of the regression lines with Bonferroni correction for the two ages indicated that 5-month-olds ($190.12 + 74.88 \log_2 n$) had a significantly steeper slope than 9-month-olds ($204.08 + 25.18 \log_2 n$), $t(96) = 4.20$, $p < 0.0001$.

Though there was a significant difference between the regressions of 5-month-olds and 9-month-olds, the analysis does not indicate whether either of the ages individually demonstrated a significant regression of saccadic RTs on bits of information. To precisely characterize whether the linear relation between the number of bits of information and saccadic RTs was significant at either age, therefore, independent regression analyses were performed separately for 5- and 9-month-olds (Vickrey & Neuringer, 2000). For 5-month-olds, the regression analysis yielded a significant relation, $r^2 = 0.62$, $F(1, 48) = 77.63$, $p < 0.001$, Cohen's $F^2 = 1.61$, indicating that saccadic RT increased with increasing bits of information. The slope of the regression line was 74.9 msec per bit, further demonstrating that saccadic RTs increased with spatial uncertainty (see Figure 4(a)). For 9-month-olds, the regression analysis also revealed a significant relation, $r^2 = 0.16$, $F(1, 48) = 9.33$, $p < 0.01$, Cohen's $F^2 = 0.19$ indicating again that saccadic RTs increased with increasing number of bits (see Figure 4B). The slope of this regression showed an increase in RT of 25.18 msec per bit, providing further support that when spatial frames were available saccadic RTs increased with spatial uncertainty.

The results from this experiment show that as the number of bits of information and uncertainty increase so do infants' saccadic RTs, both at 5 and 9 months of age, a finding consistent with the theoretical framework of speed of information processing (Sheppard &

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[1] Means of median RTs were used for two reasons, to be consistent with the measure used in Dougherty and Haith (2002) and to use a measure of central tendency that is not as sensitive to the variability that is typical in infants' saccade performance.

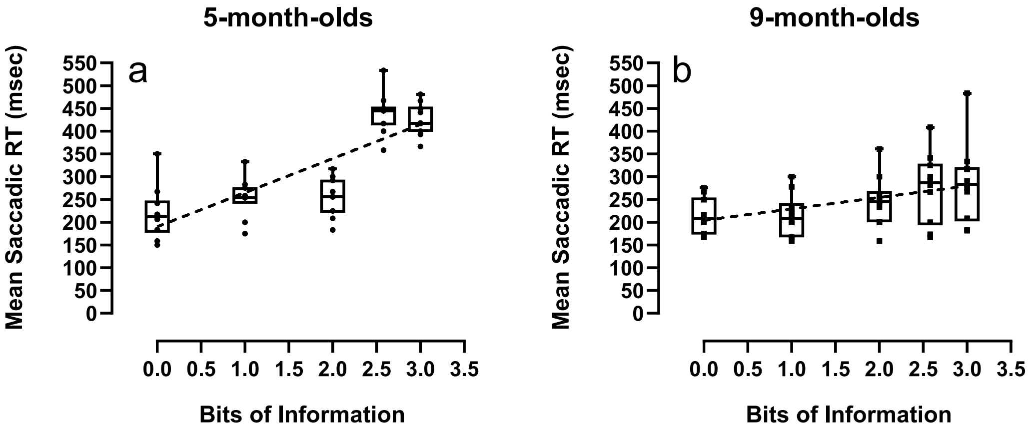

Figure 4. (a) Box plots and regression analysis for 5-month-olds' saccadic RTs plotted as a function of bits. Dashed line: $RT = 190.12 + 74.87 \log_2 n$, $p < 0.001$. (b) Box plot and regression analysis for 9-month-olds' saccadic RTs plotted as a function of bits. Dashed line: $RT = 204.08 + 25.18 \log_2 n$, $p < 0.01$. Vertical bars indicate ± SE.

Vernon, 2008). That infants' saccadic RT functions showed an increase with bits of information is a strong indication that, in contrast to adults' saccades (Experiment 1; e.g., Lawrence et al., 2008), infants' saccades are sensitive to spatial uncertainty as the greater number of alternatives available for infants' attention and processing produced a cost in their response rate and processing speed. Arguably, that effect is due to the additional time needed to make a choice as uncertainty increased (Dougherty & Haith, 2002). Furthermore, the possibility that the less mature developmental state of the younger 5-month-olds' attentional mechanisms might account for differences in their eye movements being sensitive to increasing spatial uncertainty and 7-month-olds' exhibition of increasing saccadic RTs when there were no frames (Dougherty & Haith, 2002) was not borne out as providing spatial frames to aide their attentional allocation did not facilitate their eye movements and flatten the saccadic RT function to be similar to adults' saccadic RT function.

The regression slopes, however, were significantly attenuated in 9-month-olds as compared to 5-month-olds (25.18 vs 74.87 msec per bit), demonstrating a slowing of the rate of change in saccadic RTs due to increasing bits of information. Thus, this finding suggests that when choosing a spatial target there is a gradual dissipation with age in the sensitivity of eye movements to spatial uncertainty and SIP. Decreasing the sensitivity of eye movements to uncertainty may consequently underlie the developmental discrepancy between infants' (Dougherty & Haith, 2002) and adults' (Kveraga et al., 2002) saccadic RTs where infants' saccadic RTs increase with more bits of information, but adults' saccadic RTs do not. At what age along the developmental timeline the saccadic RT function completely flattens to resemble adults' saccadic RT function remains an open question.

Comparison of regression functions of adults and infants

To further assess whether the developmental trend of decreasing sensitivity of saccadic RTs to spatial uncertainty demonstrated in infants continues toward a flattening of the function in

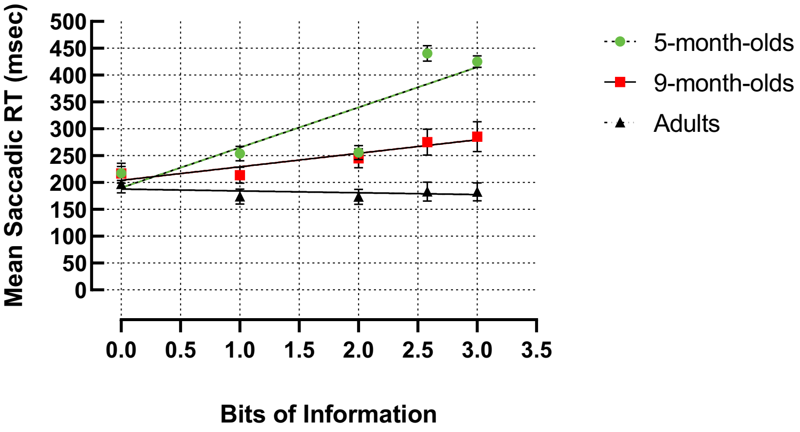

Figure 5. Comparison of regression functions of adults' and 5- and 9-month-olds' saccadic RTs plotted as a function of the number of bits. Vertical bars indicate ± SE.

adults, adults' saccadic RT functions were added to the multiple regression model. This analysis again revealed the main effects of age, $F(2, 135) = 79.98$, $p < 0.001$, $\eta_p{}^2 = 0.54$, and number of bits, $F(4, 135) = 21.24$, $p < 0.001$, $\eta_p{}^2 = 0.39$, were both significant, indicating that saccadic RTs differed across the ages and across number of bits. The interaction of age and number of bits, as a measure of slope, was also significant, $F(8, 135) = 10.44$, $p < 0.001$, $\eta_p{}^2 = 0.38$, indicating that saccadic RTs increased at different rates with increasing number of bits as a function of age, including through adults. Post-hoc comparisons of the slopes of the regression functions with the Bonferroni correction revealed that the adult saccadic RT slope ($187.77–3.41 \log_2 n$) significantly differed from the slopes for infants at both ages (5-month-olds: $190.12 + 74.88 \log_2 n$; 9-month-olds: $204.08 + 25.18 \log_2 n$; p's < 0.001) (see Figure 5).

General discussion

The primary goal of this study was to better understand the development of SIP for spatially defined items in infants relative to adults by assessing whether infants' saccades increase with increasing possible choices and spatial uncertainty (Jensen, 1987). To overcome the limitations of previous developmental research using habituation and predictable sequences of events (e.g., Bornstein, 1985, 1998; Rose, Feldman, & Jankowski, 2002, 2004) and enable more direct comparisons between infants and adults, a saccadic RT paradigm was used in the present study that was more similar to the choice reaction time tasks and measures used with adults. Across two experiments with 5-month-olds, 9-month-olds, and adults, a developmental trend was uncovered regarding the sensitivity of eye movements to spatial uncertainty, as a measure of SIP. This developmental trend was characterized by 5-month-olds having a steep increasing saccadic RT slope, whereas 9-month-olds had an attenuated but still increasing slope, and adults having a flat to a slightly decreasing slope. According to Jensen (2005), slopes are the most important means of assessing SIP and judging the efficiency of processing as the amount of information and uncertainty increases. The developmental trend appears, consequently, to be a flattening of the saccadic RT slope with age and decreasing sensitivity of eye movements to an increasing number of choices and spatial uncertainty.

Saccadic sensitivity decrease across development

The developmental trend of decreasing sensitivity of infants' saccades to spatial uncertainty would suggest that the effects of SIP have less influence on saccade initiation as the infant ages, culminating in a complete lack of influence on adults' saccades. These developmental differences may emerge because SIP is slowing with increases in spatial uncertainty due to more resources being needed to make a decision from among the choices. As infants age and their overall processing speed increases, the influence of increasing uncertainty likely lessens. For young infants, consequently, who have limited processing resources already, the impact of uncertainty and SIP may become more substantial in combination with their slower saccade initiation systems (Gredebäck et al., 2006). For adults, whose processing resources are less limited and their saccade initiation systems are relatively quick, uncertainty and SIP are not as impactful. The increase in saccadic RTs as the number of bits of information increased in the infants, however, would seem to suggest that SIP is being indexed (Jensen, 2005) and the age differences would suggest that indexing is speeding up with age. The question remains concerning the mechanism that mediates the age-related decline in saccade sensitivity to SIP.

Although this study was not designed to address and current findings cannot answer the question of what mechanism accounts for the developmental trend, theoretical accounts for why adults' saccades might not show sensitivity provide a couple of possible frameworks. One explanation for adults' lack of saccadic sensitivity relative to their exhibition of manual response sensitivity is that uncertainty and SIP do not impact the visual system's processes for identifying and selecting the stimulus target (Kveraga et al., 2002). Instead, the dichotomy in response sensitivity is suggested to reflect the engagement of response selection processes, namely, the selecting, initiating, and mapping the appropriate response (Kveraga et al., 2002). Both behavioral and neural research have shown that, except under certain circumstances, only a single stimulus-to-response mapping can occur efficiently (Jiang & Kanwisher, 2003). As a consequence, manual response selection and mapping become less efficient as the stimulus-response mapping needs to be applied to more than one possible stimulus (e.g., more choices). That adult saccades, in contrast, are insensitive to an increasing number of choices, therefore, likely reflects that their initiation of saccades under uncertainty does not require the process of response selection and mapping.

Developmentally, that infants' saccadic responses are sensitive to increasing spatial uncertainty would suggest that their saccades do require response selection before initiation, in contrast to adults' saccades. Further, that infants' saccades exhibit a decreasing sensitivity to uncertainty as they get older suggests that the response selection process has less influence on saccade initiation as development proceeds, culminating in the lack of influence of response selection on adults' saccades. This framework as plausible is supported by evidence showing that saccades are initiated faster and more accurately (Aslin & Salapatek, 1975; Canfield et al., 1997; Gredebäck et al., 2006; Hunter & Richards, 2003) as infants get older, approaching adult-like levels by the end of their first year. Additionally, the superior colliculus, which is involved in speeded stimulus-driven reactive saccades, has shown age-related changes (Richards, 2010; Stein, 1984) that might enable the production of more visually guided, automatic saccades that do not require response selection (Kveraga et al., 2002).

Infant and adult saccadic behavior on other tasks, however, gives pause to a response selection explanation. In particular, research on visual search, which can be viewed as encompassing uncertainty (e.g., Quétard et al., 2016), has found no difference between infants' and adults' pattern of saccadic responses as the set size (e.g., number of choices?) increases (Adler & Gallego, 2014; Adler & Orprecio, 2006). That the RT functions did not differ suggests that response selection may not be responsible for the developmental difference in saccade sensitivity to uncertainty. Furthermore, early SIP studies indicated that response selection and an increase in the time for adults to map their motor response to the appropriate button as the number of target choices increase could not account but for a small amount of the increase in RT (Hale, 1968; Teichner & Krebs, 1974). Hale (1968), for example, found that even though the effect of the number of choices on RT was attenuated when participants engaged in substantial amount of practice (even up to 5000 trials), when presumably such motor mapping could be instantiated, it was still sizable. Thus, a decreasing influence of response selection and mapping is unlikely to be responsible for the development differences.

Alternatively, some studies have demonstrated a reverse effect where saccadic RT decreases as choices and bits of information increases (Lawrence et al., 2008). Lawrence et al. (2008) hypothesize that this negative effect in which adults' saccadic RT decreases with increasing choices, and therefore, adults' saccades' general lack of sensitivity to spatial uncertainty is due to inhibitory processes. In this framework, during fixation of a target, eye movements to other potential targets are inhibited. To make an eye movement to another target, therefore, the inhibition must first be overcome. Lawrence et al. suggest that as the number of potential targets decreases, the likelihood of an eye movement being spontaneously elicited by any of the available targets increases, which requires a concordant increase in inhibition to prevent making a saccade precipitately. Overcoming increased inhibition requires more time, which in turn counters the effect of SIP, and thereby flattens (or reverses) the function of bits of information with saccadic RT.

If inhibitory mechanisms underlie the lack of impact of uncertainty on saccadic responses in adults, then this would suggest that in early development inhibition of prepotent saccades is not functionally mature. Further, this inhibitory account would suggest that as inhibitory mechanisms mature and initiating saccades increasingly require overcoming inhibition, then more choices and greater uncertainty would have less of an impact on saccadic responses. Consequently, saccadic RT would flatten with age, as was observed. Evidence regarding the maturation of inhibitory mechanisms in early development, however, has been mixed. Some research has provided evidence that the capacity to inhibit prepotent saccades in early infancy is limited (Wentworth & Haith, 1998) and inhibitory control mechanisms over allocating attention and saccades (Holmboe et al., 2018) seem to develop over the course of the first year. Furthermore, the development of the superior colliculus (Richards, 2010; Stein, 1984), which mediates the inhibitory mechanism, provides additional support. Other studies, such as those showing a capacity to disengage fixational attention (Butcher et al., 2000; Hood & Atkinson, 1993), however, suggest that inhibitory mechanisms are functional in early infancy and that the developmental limitations in initiating saccades relate to overcoming the inhibition to do so.

The findings of the current study that the slope of the saccadic RT function flattens with age and becomes more adult-like over the first year seem more consistent with the development of inhibitory mechanisms account. That prior attentional cueing of potential target locations with frames did not significantly impact infants' saccadic RT functions that seem to provide further support. If response selection was responsible for the developmental pattern, then providing frames should have disambiguated the response selection process and flattened the saccadic RT functions in early infancy. That frames did not flatten the saccadic RT functions suggests that response selection was not responsible. In contrast, though, if maturing inhibitory mechanisms in infancy were responsible, then providing frames about potential target locations would have no impact on saccadic RT functions as they would facilitate attention and the initiating of all saccades to targets regardless of the number of choices. Future work is needed to disambiguate these two possible accounts.

Alternative possibilities

Due to previous research demonstrating that the initiation of reactive saccades becomes faster as the infant ages (Aslin & Salapatek, 1975; Canfield et al., 1997; Gredebäck et al., 2006; Hunter & Richards, 2003), the different slopes of the saccadic RT functions as age increased could possibly be due to the age-related differences in saccade initiation. That is, the decreasing saccadic RT slope with age might be a manifestation of the developmental capacity to initiate saccades faster. If true, this would also add to our understanding of the development of saccadic RTs. Previous infant saccadic RT studies have typically used target stimuli with only one level of spatial uncertainty. Kenward et al. (2017), for example, used a target stimulus that always appeared in one of four locations (i.e., screen corners) and found only a small decrease in saccadic RT between 9 and 15 months of age. The current study extends that to multiple levels of uncertainty and demonstrates that developmental differences between ages in early infancy become more pronounced as spatial uncertainty increases. Yet despite the uncertainty differences, the current findings are consistent with recent infant saccadic RT studies in that there seems to be a larger decrease in saccadic sensitivity between 5- and 9-month olds, similar to Gredebäck et al. (2006) findings with 4- to 8-month-olds, and a smaller decrease after 9 months, similar to that found by Kenward et al. (2017).

Performance across ages in the current study, when there was a single possible choice and 100% certainty, suggests, however, that developmental differences in saccade initiation are not the source for the developmental differences exhibited in the saccadic RT functions. When there was only a single target, which represents the y-intercept and the baseline for initiating saccades in this paradigm, participants at all ages initiated saccades in the essentially same amount of time (adults: 187.7 msec; 9-months: 204.1; 5-months: 190.1). Any subsequent differences that emerged due to increasing bits of information are therefore not due to differences in the speed of saccade initiation but on the influence of uncertainty.

An additional issue that might have influenced the analysis and interpretation of the eye movement data is what might be considered a relatively small sample size for each age group. Though our power analysis indicated a sample size of 9 would be sufficient to detect the effect hypothesized, the possibility exists that the power was still too low to detect smaller effect sizes. Taking note of the effect sizes calculated for each regression, however, indicates that the effects of spatial uncertainty on saccadic RT were not small and the magnitude of that relationship is relatively strong despite the seemingly small sample size. Thus, the sample size used was sufficient to detect a meaningful effect of spatial uncertainty on saccadic RTs in infants.

Conclusions

The present study indicates that using saccadic responses to varying number of choices and spatial uncertainty can be a viable method for studying SIP for spatially defined items in infancy depending on age, as evidenced by the increase in saccadic RTs as spatial uncertainty increased with more possible choices. In contrast to other studies of SIP in infants, the strength of the present saccade measure approach is that it measures responses on the millisecond scale and when there are varying number of spatial choices. The current study was, therefore, better situated to document the development of SIP and allowed for direct comparisons of SIP abilities between adults and infants. The increased time cost with saccadic responses, however, became attenuated as infants aged from 5 to 9 months and disappeared by adulthood. Sources for this developmental trend may reflect increasing automaticity of the processes underlying saccadic responses, and less reliance on response selection rendering eye movements less sensitive to uncertainty and changes in SIP or may be due to increased functioning of inhibitory mechanisms related to initiating saccades.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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