



A computational vector-map model of neonate saccades: Modulating the externality effect through refraction periods

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ABSTRACT

The present study develops an explicit and predictive computational model of neonate saccades based on the interaction of several simple mechanisms, including the tendency to fixate towards areas of high contrast, and the decay and recovery of a world-centered contrast representation simulating a low-level inhibition of return mechanism. Emergent properties similar to early visual behaviors develop, including the externality effect (or tendency to focus on external then internal features). The age-associated progression of this effect is modulated by the decay period of the model's contrast representation, where the high-level behavior of either scanning broadly or locally is modulated by a single decay parameter.

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1. Introduction

Intuitively, developing an explicit and predictive computational model of saccadic eye movements seems an intractable task. Were we to record the saccades of a number of participants while viewing the same selection of natural photographs with no particularly common theme, we would rightfully expect that while the participants may tend to look at many of the same objects within those photographs, the specific pattern of saccades while viewing a given photograph would be unique for each individual. As such, recent models (e.g. Itti and Koch (2001); see Heinke and Humphreys (2005), for a review) tend to focus on modeling visual saliency – where one is more likely to direct visual attention – rather than developing explicit models of saccades. Why then, when it could be convincingly argued that an individual's pattern of saccades (over long periods of time and for natural images) is unique, might we go to the trouble of coming up with a model that generates such a pattern of saccades?

Neonates, we might argue, may present a less intractable challenge for such a model.

While the visual system of even young infants has had many thousands of hours of unique visual experience to develop, tune, and form preferences, the visual system of newborns is very much closer to the “seed” of neural mechanisms that eventually grow into a complete perceptual modality. While contemporary research

tends to focus on infants of at least 1 month of age, the classic studies by Haith (1980) extensively observed newborn visual attention. Haith formulated an explicit series of “rules that babies look by”, and placed these rules in the context of a low-level neural framework. The spirit of Haith's investigation is an attempt to describe how a combination of very simple mechanisms may give rise to what, at the surface, is some large subset of the complex behavior of neonate saccades.

Haith (1980) has suggested that newborns are “creatures of preference” and are active participants in their visual scanning behavior. The newborn is capable of forming preferences (tempered by their poor visual ability) and attending to stimuli that are congruent with these preferences. After extensive research into the visual scanning behavior of human infants, Haith has emphasized five particular systematic “rules” that govern neonate saccade patterns. These rules postulate that when presented with a given visual field, infants engage in a broad directed search for “bold contours,” or areas of high contrast. When such a region is encountered, infants tend to focus their saccades within the general vicinity of the contour, repeatedly implementing eye movements that cross over the contour in a zig-zag fashion. Similarly, in terms of progressively more complex visual stimuli, Salapatek and Kessen (1966) found that newborns tend to fixate more towards the edges and vertices of triangles, while only infrequently fixating towards the interior of the shape – a pattern similarly interpreted as a preference in the newborn towards regions of contrast (or, rapid shifts in brightness between nearby regions) within an image. In addition to geometric shapes, neonate saccade patterns have been recorded in response to the presentation of the human face. Maurer and Salapatek (1976) found that all of

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their 1-month-old participants tended to fixate on the peripheral or external features of a face as opposed to the inner features, not unlike the pattern of saccades observed with geometric shapes. This tendency to focus on the perimeter of the face decreased over the course of development, as 2-month-old participants were equally likely to fixate on either peripheral or internal features. Infants of both ages fixated more often on the chin and the hairline of the face than the ears, while similarly Haith, Bergman, and Moore (1977) found that older infants (7-, 9-, and 11-month-olds) were more likely to fixate on the eyes, whereas younger infants' saccades tended to be localized towards the edges of the face. These saccade patterns are indicative of an externality bias in neonates, where the young infant tends to focus on external, rather than internal, features of a stimulus.

While many of the temporal and spatial properties of infant saccades resemble those of adults, (e.g. Garbutt, Harwood, & Harris, 2006; Hainline, Turkel, Abramov, Lemerise, & Harris, 1984), there are a number of qualitative differences. Infant saccades are often characterized by the presence of "oscillations" – back-and-forth eye movements in opposite directions, generally more likely to occur in the horizontal plane than the vertical. Interestingly, the velocity profiles of these oscillations suggests that they are full saccades and not smaller, corrective eye movements, and as such these oscillations may reflect lapses in attention and/or changes in arousal (Hainline et al., 1984). While infant saccades may be prone to oscillation, Aslin and Salapatek (1975) observed that the saccades of very young infants (1- to 2-month olds) often fall short, occasionally taking several short hypometric saccades to successfully fixate upon a peripheral target. Aslin and Salapatek interpret the presence of these short successive saccades to reflect the immature saccadic generation system in infants.

While we have described infant saccades in terms of their behavior in response to a stimulus, the production of saccades in adults is thought to be driven by a combination of stimulus driven (or bottom-up) properties interacting with higher-level (or top-down) cognitive planning. Evidence suggests that there are two distinct brain systems responsible for controlling eye movement behavior (Richards, 2001; Schiller, 1998). The first system, responsible for controlling reflexive saccades to peripheral stimuli, is localized to both the lateral geniculate nucleus and superior colliculus, and is thought to be fairly mature at birth. The second system, hypothesized to coordinate the high-level control of voluntary saccades with visual attention, involves aspects of the visual cortex, parietal cortex, as well as the frontal-eye-fields, and progressively develops over time. In an attempt to dissociate these two systems, Richard and Holley (1999) investigated the developmental trajectory of smooth pursuit eye movements.

Interestingly, saccades directed toward the tracking target during periods of inattention (determined by heart rate) were nearly at adult-level performance in young infants. However, attention-directed saccades and smooth pursuit movements thought to be representative of the high-level voluntary saccade system showed a marked increase in performance with age. While these data would seem to suggest that the two systems are developmentally dissociable, the story is at least a little more complicated. In the visual expectation procedure (Haith, Hazan, & Goodman, 1988), stimuli are presented that follow a regular, predictable pattern. Using this procedure, Wentworth and Haith (1998) found that infants 2–3 months of age are capable of making predictive eye movements that are consistent with the systematic pattern of visual stimuli. This suggests that even young infants may be able to make voluntary predictive saccades, and suggests the two neural systems supporting eye movements may not follow entirely independent developmental trajectories. That being said, it is unclear whether these "expectations" are driven by higher-level cortically mediated preferences, or whether they simply represent an

implicit sensitivity to systematic regularities. Nevertheless, it seems likely that infants can capitalize on environmental regularities or predictive relations, at least in some paradigms.

With respect to modeling visual attention, contemporary approaches tend to take a hybrid development path, incorporating both stimulus driven and higher-level concepts. Rather than explicitly modeling saccades, these models tend to be stochastic in nature, and instead focus on generating a map of "visual saliency" (or, the probability of fixating in a given region) from the low-level stimulus characteristics of a given visual field. Koch and Ullman (1985) and Itti and Koch (2001) describe two such computational models of adult saccades in which attention is directed to elements of a visual scene that are determined to be highly salient or visually "interesting". In their model, Itti and Koch propose an analog to the organization of visual cortex, whereby a parallel array of linear filters tuned to specific low-level visual features such as orientation, contrast, and intensity, emulate the sensitivity of cells in V1. The output of these initial filters is then passed onto a second level whereby maps of other non-linear properties of the visual system (such as centre-surround antagonism, or lateral inhibition) are generated. The resulting feature maps are then combined to produce a "saliency map" of the visual scene, describing the probability for visual attention to be deployed at any given point on an image. Here, attention is guided not only by the interplay between regions of high saliency, but also an inhibition of return mechanism (Posner & Cohen, 1984) that biases the observer from returning to regions that were previously fixated upon.

Modelling adult saccadic behavior necessarily requires the integration of high-level cognitive processes with low-level bottom-up mechanisms (Henderson, Brockmole, Castelano, & Mack, 2007). However, where an adult uses a body of prior knowledge coupled with salient bottom-up stimulus features to guide their visual search of a scene, one might convincingly argue that the saccadic behavior of neonates – unable to draw from at least a majority of higher-level visual attention processes – is largely stimulus driven, and far closer to the "seed" of neural mechanisms underlying low-level visual orienting. From this perspective, and in the spirit of Haith's (1980) attempt to describe the seemingly complex behavior of neonate saccades in terms of the interaction of a number of simple low-level processes, the present study aims to develop a sketch of a predictive, qualitative computational model of neonate saccades.

2. Model algorithm and description

We present a predictive, qualitative computational model of neonate saccades. The model combines several simple low-level mechanisms, including the tendency to implement saccades towards areas of high contrast, and the concept of saturation and refractory periods in a world-centered representation of contrast. The interaction of these mechanisms produces a single saccade vector at each epoch, where these individual saccade vectors are progressively overlaid upon an image to produce a large pattern of saccades over the runtime of the model.

2.1. Contrast and the visual world

The observations by Haith (1980) speak of contrast, rather than illuminance or colour, as a central contributor to the neonate's pattern of saccades. As such, the model takes a bitmap image as input, first converting this image to grayscale, then uses this grayscale image to create a "contrast map" that serves as the possible visual world of the model. Here, contrast is defined as the variance in illumination over a small region of pixels. For a given pixel, the model

calculates this contrast value as the sum of the differences between the intensity values for each pixel in a 3×3 array (centered on the pixel of interest), and the mean illumination value of that 3×3 array:

$$\text{contrast}_0(x, y) = \sum_{i=x-1}^{x+1} \sum_{j=y-1}^{y+1} \left| \text{illumination}(i, j) - \left(\frac{1}{9} \sum_{a=x-1}^{x+1} \sum_{b=y-1}^{y+1} \text{illumination}(a, b) \right) \right| \quad (1)$$

where the contrast values across an image are normalized to be between 0 and 1.

2.2. Moving towards and crossing edges

Haith (1980) notes that neonates tend to implement eye movements that move toward then “cross over” edges, which are areas of high contrast. To implement this pattern of saccades, a small subset of the contrast map centered about the model’s current “focus” is taken as the model’s “fovea”. From this foveal field, a single saccade vector is calculated based on a weighted sum of the contrast value of each pixel, and that pixel’s distance from the center of fixation:

```

vec_x = 0; vec_y = 0;
for i = -(fovea_size/2) to (fovea_size/2)
  for j = -(fovea_size/2) to (fovea_size/2)
    saccade_vec_x = saccade_vec_x + fovea(i, j) * i;
    saccade_vec_y = saccade_vec_y + fovea(i, j) * j;
  end
end
end
    
```

where pixels that are of greater contrast, and of greater distance from the center of fixation, will “pull” the saccade vector proportionally more in their direction relative to the center of fixation. If the length of this saccade vector is greater than some threshold, the vector length is clipped to prevent global sweeps of the visual field in a single epoch.

2.3. Decreasing intensity of contrast response

The model implements a mechanism to decrease the output of the contrast map around the area of current fixation, simulating a saturation and refraction period in the neural firing of a world-centered contrast representation. This mechanism also has the

secondary effect of “keeping the model moving”, where the model’s focus will tend to progressively scan along edges or around contours as the neurons representing contrast response near its last focus saturate, produce less output, and subsequently exhibit less influence on the saccade vector. Regions of the contrast map that are within the model’s foveal field decay each epoch as follows:

$$\text{contrast}_{\text{resp}}(x, y) = \text{contrast}_{\text{resp}}(x, y) \cdot k_{\text{decay}} \quad (3)$$

while regions outside of the foveal field progressively recover their original contrast response values:

$$\text{contrast}_{\text{resp}}(x, y) = \text{contrast}_0(x, y) - [k_{\text{decay}} \cdot (\text{contrast}_0(x, y) - \text{contrast}_{\text{resp}}(x, y))] \quad (4)$$

The full workflow of the model is shown in Fig. 1. During simulations, an input bitmap is supplied to the model, from which the contrast map is generated. At a given epoch, the model populates the fovea map based on a subset of the contrast map surrounding the current fixation point. From here, the model computes a saccade vector based on the contrast present in the fovea map based on Eq. (2). This saccade vector is both displayed on an output overlay of the original bitmap, as well as used to calculate the model’s fixation point for subsequent epochs. Finally, the contrast map is updated such that values within the current fovea map region will decay according to Eq. (3), while any decayed values outside the fovea map region will progressively recover their original values according to Eq. (4).

3. Results

3.1. Constant simulations

The results of several simulations are displayed in Fig. 2. In all simulations the fovea size was 40×40 pixels, the saccade vector clipping threshold was one half the fovea size (20 pixels), while the contrast response decay constant k_{decay} varied from 0.5 to 1.0. An interesting observation is that these saccade patterns appear to focus on the general outlines of objects, while occasionally focusing on internal features – a pattern similar to the development of the externality effect (Maurer & Salapatek, 1976), where young infants tend to focus on the outlines of shapes, while progressively attending more to the internal features of those shapes by 2–3 months. Here, as the decay constant decreases towards zero, the model tends to make broad sweeps of areas of high contrast present in the visual field, quickly transitioning between

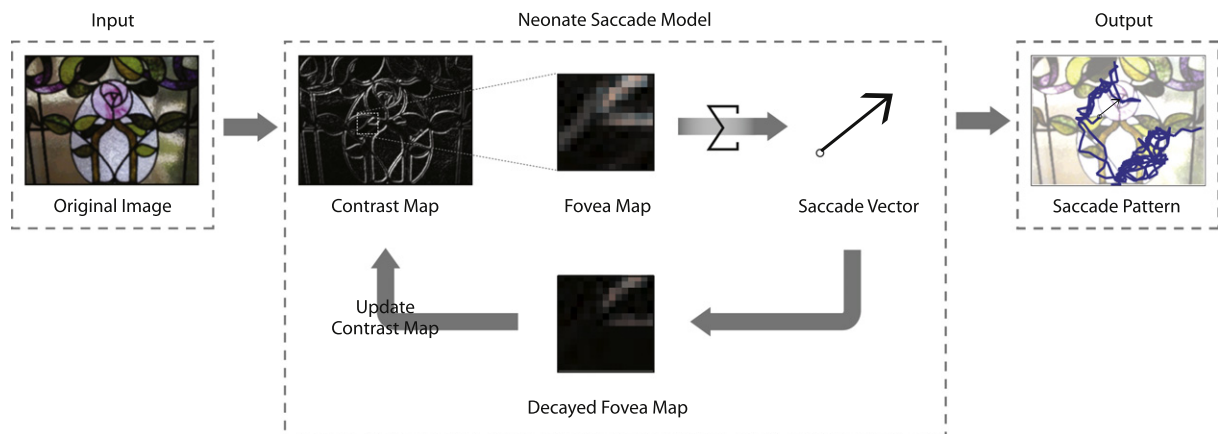


Fig. 1. A schematic workflow of the neonate saccade model. A bitmap image is taken as input, from which that serves as the possible visual world for the model. From this contrast map, a small subset is taken as the model’s “fovea map”, or current visual focus. The model then progressively generates a series of saccades, both overlaying those saccades upon the original image, and using new saccade locations to update the contents of the “fovea map”.

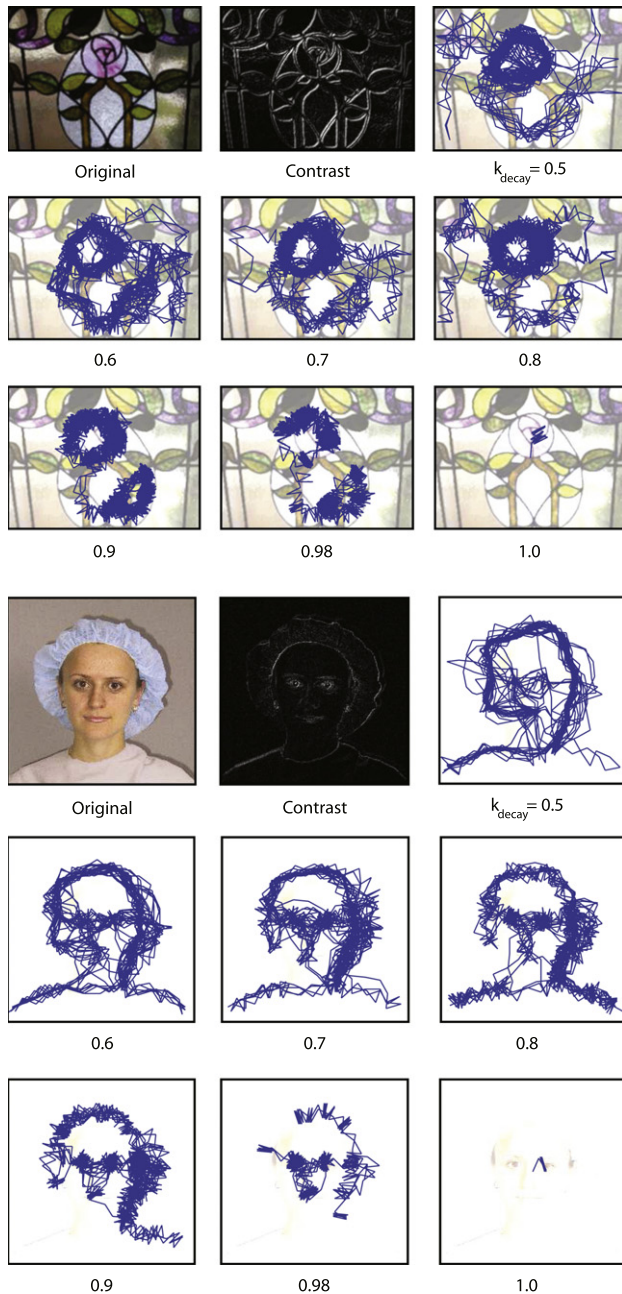


Fig. 2. Saccade patterns for two sample photographs, a stained-glass window (image size: 251×187), and a female face (image size: 250×248), over a variety of decay constants. The model tends to scan broadly with lower-decay constants, following the outlines of the head and shoulders in the facial image, and many of the borders in the stained-glass image. As the decay constant increases, signifying contrast receptors with a progressively shorter refractory period, the model tends to remain in local areas of high-contrast, focusing on the internal facial features (facial image) and central flower figure (stained-glass image). Each graph represents 1000 saccades, where the first saccade of each graph originated from the image's center.

different regions of the image. Similarly, as the model's decay constant approaches 1.0, the model tends to transition from scanning the global outlines of objects, instead focusing on a single local region of high contrast and complexity.

In the spirit of studying the seemingly high-level behaviors exhibited by the interaction of simple mechanisms, we then consider how the active online modulation of one or two of the model's parameters could generate qualitatively different patterns of scanning. To illustrate this, consider an experiment where the above sac-

cade generation model is some subset of a more complex model, with the following change: the "decay constant", instead of being static, is able to be modulated online and is relabeled the model's "current interest level". One could imagine this more complex model containing a number of simple mechanisms to increase this interest level in the presence of particular types of stimuli – perhaps those of a certain colour, symmetry, or (in a significantly more complex model) those with a tendency towards motion. The model could then direct its attention towards certain types of stimuli, occasionally switching its attention when it loses "interest".

3.2. Active modulation simulations

While such a complex model is beyond the scope of this work, the current model could be modified to emulate some of this behavior. Replacing the constant decay parameter with a sinusoidal function can be thought of as mimicking a process of finding a stimulus particularly interesting (increasing k_{decay} towards 1.0), then progressively losing interest and finding another portion of the image to attend to (decreasing k_{decay} towards zero). Fig. 3 illustrates the result of several simulations with such a sinusoidal decay function, of the form:

$$k_{\text{decay}} = b + [A \cdot \sin(\omega t)] \quad (5)$$

where, for all active modulation simulations, b was set to 0.75, and A to 0.25, such that the decay function oscillated from 0.5 to 1.0 – values that were empirically determined from the constant simulations to reflect both broad sweeps of the visual field on one end of the spectrum, as well as focus towards particular features at the other end. Through pilot simulations, an angular frequency ω of 20, corresponding to approximately 55 transitions from 1.0 to 0.5 then back again over the course of 1000 saccades, was used. In terms of the qualitative patterns of saccades, in all 10 sample faces the model tended to locate and implement saccades that followed nearly the entire perimeter of each face. The model also located and transitioned between internal features, such as the eyes, nose, and mouth, in eight out of the 10 sample faces.

4. Discussion

4.1. Interpretation

In this model, the externality effect (Maurer & Salapatek, 1976) is likely mediated by the interaction of several simple mechanisms: (1) the tendency for the model to follow along continuous contours, due to the decreasing intensity of contrast response in a world-centered contrast representation, (2) the tendency for objects in a scene to contrast from their surroundings, producing a continuous high-contrast region around their borders, (3) the tendency for objects (and environments) to themselves have local areas of high-contrast features, which the model can often follow until a continuous, high-contrast object border is encountered, and (4) the tendency for the model to explore larger areas of the visual field when the decay constant is such that familiar areas do not quickly recover their full contrast response levels. The virtue of this argument is that a seemingly very high-level behavior – the idea of implementing saccades that focus either on the general perimeter of faces, or on both the perimeter and internal features – is controlled, in this model, by only a single decay parameter. From the model's perspective, this age associated transition from attending primarily to external features towards attending to both internal and external features would reflect the infant's newfound ability to modulate the decay period of the neurons involved in maintaining a world-centered contrast representation.

While the model is inspired by Haith's (1980) investigation of neonate saccades and is able to produce saccade patterns that

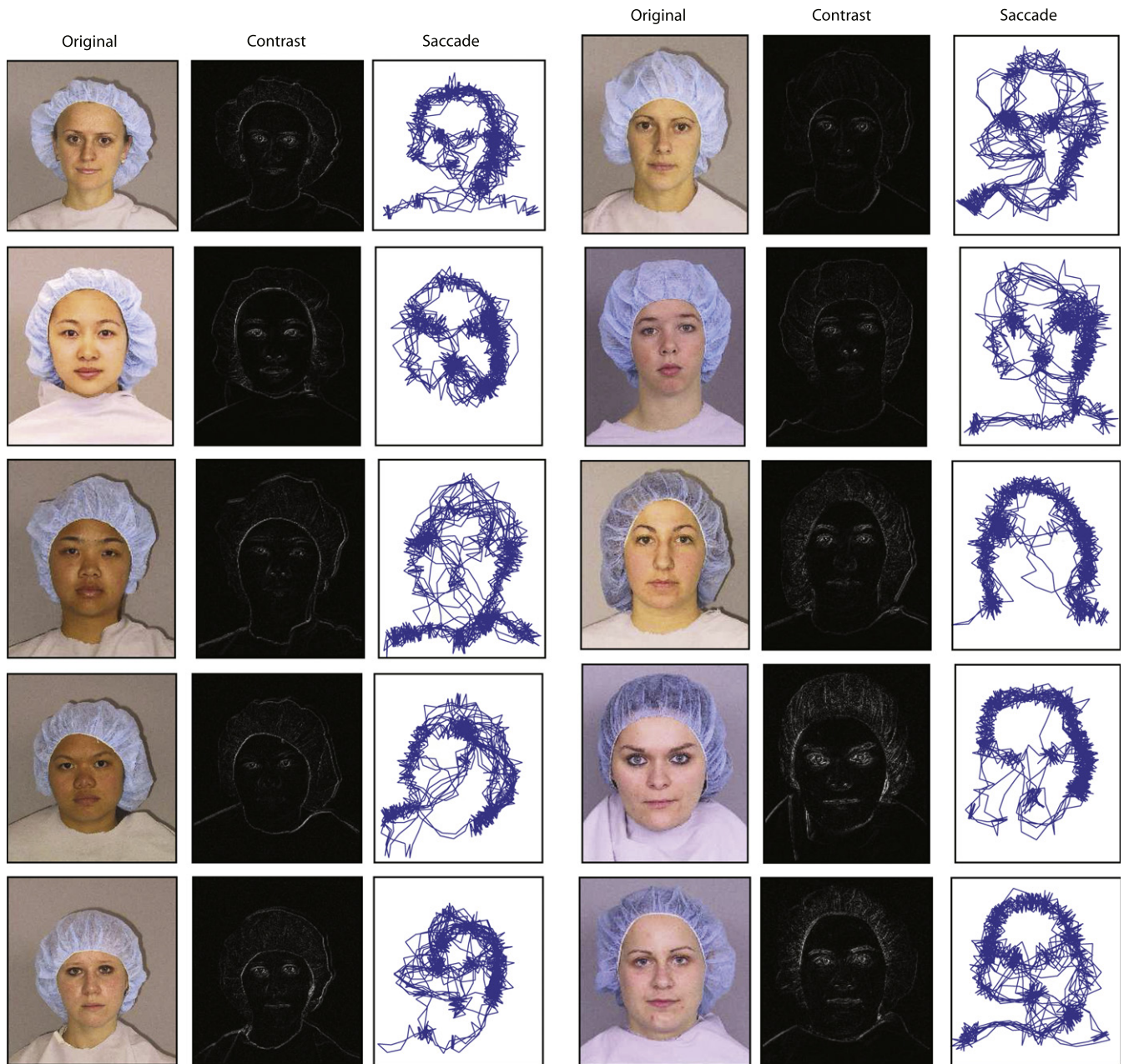


Fig. 3. Saccade patterns for 10 sample female faces in the active modulation simulation. The model tends to scan both the perimeter and internal features of the faces, locating internal features such as the eyes and mouth.

qualitatively resemble the developmental progression of the externality effect in young infants viewing natural images of faces, how well can the model account for the saccade patterns of newborns when viewing artificial images? Salapatek and Kessen (1966) found that newborns tend to get “stuck” on salient aspects of images, such as a single vertex of a triangle, and as a result often fail to explore large subsets of their visual field. To examine whether the model also exhibits this effect, a follow-up simulation was conducted using an image of a triangle as visual input (similar to the stimuli that Salapatek and Kessen used with newborns). The results are displayed in Fig. 4.

The results show that whether k_{decay} is constant or actively modulated, the model tends to scan around the perimeter of the triangle in all cases except one – where k_{decay} is set to 1.0, a situation where there is no decay. In this no decay case, the model qualitatively emulates the behavior of newborns becoming fixated upon a single

vertex as the model’s fixation quickly settles to a convergence region in the contrast map where the saccade vector is continually “tugged” back and forth around the vertex. Without decay, the model is essentially limited to the use of a retinotopic representation of contrast, and no longer contains an inhibition of return mechanism to selectively inhibit temporally familiar areas.

Interpreting the results across all simulations, a significant subset of newborn visual scanning can be qualitatively modeled with a simple vector-sum mechanism operating over a world-centered representation of contrast in the visual world, where the contrast response of this representation selectively decays and recovers according to a single decay parameter. In the case where this decay parameter is not present, the model is unable to inhibit the contrast response of the current foveal map or to take the inhibition (and recovery) of previous foveal maps into account. This mechanism essentially emulates a retinotopic rather than world-centered

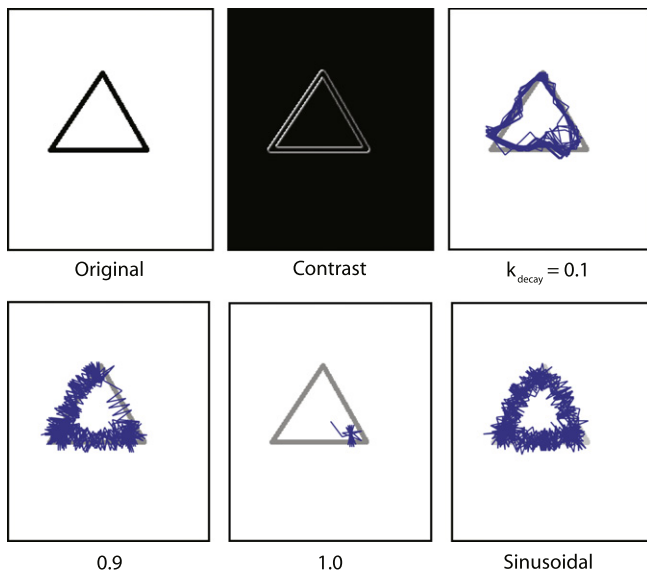


Fig. 4. Saccade patterns for a triangular stimulus similar to those used by Salapatek and Kessen (1966), under both constant and sinusoidal k_{decay} values. The model tends to implement saccades that scan the perimeter of the triangle in each case except where k_{decay} is set to 1.0 – in this case there is no decay, and the model tends to fixate toward a single vertex of the triangle, failing to explore the rest of the display.

representation, and qualitatively accounts for Salapatek and Kessen's (1966) newborn saccade patterns. This suggests that a progressive shift from a retinotopic representation of contrast without the capability of decay to a world-centered representation of contrast response supporting the saturation and recovery of specific regions of the visual world manifests itself behaviorally as the developmental progression from first becoming stuck on local salient features of objects (no decay), to focusing on the external boundaries of objects (constant and intense decay), to finally being able to actively scan both the internal and external features of objects (the active modulation of decay). This is consistent with research that suggests that young infants (at approximately 6 months) are able to use world-centered representations to guide their actions (Clifton, Muir, Ashmead, & Clarkson, 1993; Gilmore & Johnson, 1997a, 1997b; von Hofsten, 1980), where the development of a world-centered frame of reference from a more limited retinocentric frame of reference is suggested to be the result of cortical maturation processes that allow the infant to represent the world in a more sophisticated manner. Specifically, areas within the parietal cortex have been shown to integrate information from retinocentric maps of the visual field with kinesthetic information from head, eye, and body movements to maintain a stable world-centered representation of the visual world (Andersen, Snyder, Li, & Stricanne, 1993; Cohen & Andersen, 2002), and these cortical areas appear crucial both to forming representations from different frames of reference (Duhamel, Colby, & Goldberg, 1993), and to maintaining a short-term coordinate-specific representation of space to guide efficient interaction with the environment (Stein, 1989).

4.2. Predictions

Where areas within the parietal cortex are responsible for remapping visual information from retinal coordinates to world-centered coordinates, lesions to these areas would likely disrupt the ability to represent the environment in a world-centered frame of reference and may result in visual targeting that is primarily retinotopically based, emulating the saccadic behavior of neonates.

There is some evidence to suggest that this is the case with hemi-neglect patients who have parietal damage, where these patients tend to refixate upon old locations in a visual search task (Mannan et al., 2005; Parton et al., 2006; Husain et al., 2001), possibly as a result of their impaired spatial working memory (Wojciulik, Husain, Clarke, & Driver, 2001), or an inability to re-map the retinal coordinates of the display into more complex frames of reference (e.g. Sapir, Hayes, Henik, Danziger, & Rafal, 2004). On the surface, this saccade behavior qualitatively resembles the saccade behavior of very young infants, and is simulated in our model before the neonate has the capability of supporting a world-centered representation of the visual world with selective decay and recovery of specific spatial regions. If patients cannot maintain a global representation of a display while searching, or if they are unable to decay their global representations of a display, then the model would predict that their saccades would likely return to previously fixated regions of space, neglecting large regions of the display – or at least, in the case of partial damage, any regions of the display that they are unable to maintain world-centered representations of.

From the perspective of stimulus features, the model's contrast-seeking mechanisms make a key assumption about the statistics of natural images, or at least the faces and other images that are used in experiments that find the externality effect in newborns – namely, that the highest and most continuous regions of contrast will tend to occur around the perimeter of objects, such as faces, that contain internal features. The model would predict that for images where this assumption is not met, such as in the case of a face present amidst a complex high-contrast background texture such as a checkerboard pattern, that infants may have difficulty attending to the perimeter of the face. Specifically, with a lack of binocular cues to aid in object segregation and with only contrast as a guide, the model would likely follow any continuous high-contrast region and attend to a complex background texture a great deal – particularly in the case where this background texture contains more local regions of high contrast than the perimeter and internal features of a given face. Further, the model would predict that by artificially manipulating the distribution of contrast within an image, it should be possible to modulate the temporal progression of the externality effect. Specifically, were the contrast of the internal features of a face to be artificially raised or lowered, the frequency and duration of an infant's focus on those internal features relative to the external perimeter of a face should too be increased or decreased.

4.3. Connectionist modelling and inhibition of return mechanism

While the model is neurally inspired and incorporates neural principles such as refractory periods, the model itself is implemented mathematically, rather than in a connectionist (e.g. Rumelhart, McClelland, & PDP Research Group, 1986) system. That being said, the key components may be very naturally expressed as a connectionist system in the following way. A two-dimensional grid of connectionist nodes, representing the fovea, would connect to a series of four "movement" or saccade nodes (or clusters of nodes), one for each of the cardinal directions: left, right, up, and down. Each node in the two-dimensional fovea grid would connect to two of the saccade nodes – one each of left or right, and up or down. The connection weight between a given fovea node and a saccade node would follow Eq. (2), where nodes that are further from a principle axis would have proportionally more weight than those closer to an axis, implementing the mechanism of "pulling" the saccade towards areas of high contrast present in the edges of the foveal map. An interesting mechanism in the model is its method for implementing the concept of "inhibition of return" (Posner & Cohen, 1984), a concept often implemented in salience models (e.g. Itti & Koch, 2001). Here, a similar behavior of avoiding repeatedly

fixating upon temporally familiar areas is achieved, but this mechanism is accomplished using saturation and recovery periods, instead of inhibitory connections. In addition, the modulation of the k_{decay} parameter allows precise control over this effect – where k_{decay} is set close to zero, the contrast map will decay and only very slowly recover its original values, dramatically decreasing the likelihood the model will again soon fixate upon the decayed region. Similarly, where k_{decay} is set close to one, the contrast map will quickly recover its original values, and the “inhibition of return” mechanism will be far weaker, allowing a much greater chance that fixations will quickly return to a given region.

4.4. Limitations and future extensions

Under the assumption that neonate saccades are largely driven by low-level stimulus properties, it is important to take into account infants’ poor spatial vision when modeling saccade behavior. Neonates are born with extremely immature visual systems, and it has been argued that both cortical immaturities and physiological limitations of the human eye at birth are responsible (Bronson, 1974; Banks & Bennett, 1988). For example, while the spacing of foveal cones in the adult is approximately 0.58 arcmin, the neonate foveal density is much less – approximately 2.3 arcmin – significantly reducing their spatial resolution. Similarly, an additional significant pre-neural limitation of neonate vision is the light-catching ability of the foveal cones, where neonate cones tend to absorb approximately 1/350th the number of photons as adult cones (Banks & Bennett, 1988). Visual acuity at birth is poor, at approximately 20/250 in Snellen notation (Banks & Salapatek, 1978) with a peak contrast sensitivity of 2.5–9 cycles/degree in the first 2 months of life (Norcia, Tyler, & Hamer, 1990). While contrast sensitivity develops relatively quickly across low spatial frequencies, the development of sensitivity to high spatial frequencies is significantly hampered by optical immaturities (Norcia et al., 1990), and neonates appear capable of perceiving only low spatial frequencies within any given visual stimulus. With these and other empirically determined optical limitations incorporated into their model, Banks & Bennet, 1988 and others (e.g. Candy, Crowell, & Banks, 1998) demonstrate that the difference between adult and neonate contrast-sensitivity functions is due in large part to pre-neural immaturities in the neonate visual system. In light of these limitations, the high spatial-frequency contrast extraction function used in this model has a resolution of approximately 0.2° of neonate visual angle per pixel, such that the input images used across all simulations represent approximately 40–60° of visual angle.

With respect to field of view, the model currently contains a simple, artificial, and arbitrary square-shaped boundary between areas of the visual field that will contribute to the foveal map (and whose contrast responses will decay), and areas of the visual field that will remain outside the foveal map (and whose contrast responses will recover). Intuitively, one would imagine that a Gaussian window centered about the model’s current fixation would offer a more biologically-plausible foveal window than the current square-shaped window with sharp boundaries, however implementing such a graded window has the potential to interact with several of the model’s mechanisms. The current saccade vector generation mechanism relies on points of the foveal map that are progressively more distant from the center of fixation to generate proportionally larger “tugs” on the direction of the saccade vector, where selectively reducing the influence of more distant points in the fovea map according to a Gaussian distribution conflicts with this mechanism. Similarly, the contrast response for each point along a Gaussian foveal window would be in partial states of both decay and recovery, introducing non-trivial dynamics into the contrast response function. As such, resolving the conflicts of

the foveal interface boundary and incorporating these into a more general model of the periphery is left for future work.

Further, the model’s current saccade mechanism is driven entirely by contrast present in the visual world – and while this mechanism should produce saccades for most natural images, there are boundary conditions for homogenous or completely symmetrical foveal maps where the contrast present in all directions of the foveal map will sum to a zero-length vector, and not result in a saccade. In practice, for natural images, this situation is unlikely to occur, where even the noise present in a picture of a homogeneous field may be enough to keep the model’s fixation moving, albeit slowly. In either case, Haith’s (1980) rules suggest that in fields of homogeneous contrast, infants will implement a broad scan of the visual field, and in this respect the model is still incomplete.

In the spirit of Haith’s original investigation, it would be particularly interesting to explore what subset of the seemingly high-level activity of early saccades and orienting visual attention could be explained through the interaction of a handful of simple visual processes with parameters the infant is progressively more able to tune. From a higher-level perspective, even very young infants tend to have biases or preferences for stimuli of particular types, such as a preference for edges of a particular orientation (Haith, 1980; Kessen, Salapatek, & Haith, 1972), or a preference for complex stimuli presented in the upper, rather than the lower, visual field (Simion, Valenza, Cassia, Turati, & Umiltà, 2002). Were this model to serve as a starting point for generating explicit neonate saccade patterns, future high-level extensions might examine what further subset of the seemingly high-level behavior of infant saccades can be accounted for through incorporating an inborn preference to particular stimulus characteristics.

In summary, we present a predictive, qualitative computational model of neonate saccades. The model combines several simple mechanisms, including the tendency to implement saccades towards areas of high contrast, and the concept of saturation and refractory periods in the contrast response of a world-centered contrast representation. The interaction of these simple mechanisms produces saccade patterns that are qualitatively similar to those observed in neonates, both in terms of their tendency to fixate upon a single salient aspect of an image, and the tendency for slightly older infants to focus on the external as opposed to internal features of faces. Further, by modulating a single parameter governing the refractory period of a world-centered contrast representation the model can generate qualitatively different patterns of scanning, emulating the age-associated progression of the externality effect.

5. Code base

The MATLAB source code for the simulations presented in this article is available from <http://cogsci.mcmaster.ca/~peter/neonate/>.

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Appendix A

In both simulations, input bitmap images were generally between approximately 200 and 300 pixels on each dimension, and scaled low-resolution versions of high-resolution originals. Where face stimuli were used, these stimuli were cropped to be approximately centered within the input image. As pilot simulations showed that stray hairs may quickly lead the model’s fixation

towards the edge of the image, models wore bathcaps to reduce this possibility. The model's visual space contained a wide blank frame around the image to functionally prevent the generation of a fixation beyond the border of the image. The initial fixation point was at the center of each bitmap, and proceeded for 1000 epochs unless otherwise stated.

References

- Andersen, R. A., Snyder, L. H., Li, C., & Striccanne, B. (1993). Coordinate transformations in the representation of spatial information. *Current Opinion in Neurobiology*, 3, 171–176.
- Aslin, R. N., & Salapatek, P. (1975). Saccadic localization of visual targets by the very young human infant. *Perception & Psychophysics*, 17, 293–302.
- Banks, M. S., & Bennett, P. J. (1988). Optical and photoreceptor immaturities limit the spatial and chromatic vision of human neonates. *Journal of the Optical Society of America*, 5, 2059–2079.
- Banks, M. S., & Salapatek, P. (1978). Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. *Investigative Ophthalmology & Visual Science*, 17, 361–365.
- Bronson, G. W. (1974). The postnatal growth of visual capacity. *Child Development*, 45, 873–890.
- Candy, T. R., Crowell, J. A., & Banks, M. S. (1998). Optical, receptor, and retinal constraints on foveal and peripheral vision in the human neonate. *Vision Research*, 38, 3857–3870.
- Clifton, R. K., Muir, D. W., Ashmead, D. H., & Clarkson, M. G. (1993). Is visual guided reaching in early infancy a myth? *Child Development*, 64, 1099–1110.
- Cohen, Y. E., & Andersen, R. A. (2002). A common reference frame for movement plans in the posterior parietal cortex. *Nature Reviews Neuroscience*, 3, 553–562.
- Duhamel, J. R., Colby, C. L., & Goldberg, M. E. (1993). The updating of the representation of visual space in parietal cortex by intended eye movements. *Science*, 255, 90–92.
- Garbutt, S., Harwood, M. R., & Harris, C. M. (2006). Infant saccades are not slow. *Developmental Medicine & Child Neurology*, 48, 662–667.
- Gilmore, R. O., & Johnson, M. H. (1997a). Egocentric action in early infancy: Spatial frames of reference for saccades. *Psychological Science*, 8, 224–230.
- Gilmore, R. O., & Johnson, M. H. (1997b). Body-centered representations for visually-guided action emerge during early infancy. *Cognition*, 65, B1–B9.
- Hainline, L., Turkel, J., Abramov, I., Lemerise, E., & Harris, C. M. (1984). Characteristics of saccades in human infants. *Vision Research*, 24, 1771–1780.
- Haith, M. M. (1980). *Rules that Babies Look By: The organization of newborn visual activity*. New Jersey: Lawrence Erlbaum Associates, Inc.
- Haith, M. M., Bergman, T., & Moore, M. J. (1977). Eye contact and face scanning in early infancy. *Science*, 198, 853–855.
- Haith, M. M., Hazan, C., & Goodman, G. S. (1988). Expectations and anticipation of dynamic visual events by 3.5 month-old babies. *Child Development*, 59, 467–479.
- Heinke, D., & Humphreys, G. W. (2005). Computational models of visual selective attention: A review. In G. Houghton (Ed.), *Connectionist models in psychology*, pp. 273–312. Psychology Press.
- Henderson, J. M., Brockmole, J. R., Castelano, M. S., & Mack, M. (2007). Visual saliency does not account for eye movements during visual search in real-world scenes. In R. P. G. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 537–562). Elsevier.
- Husain, M., Mannan, S., Hodgson, T., Wojciulik, E., Driver, J., & Kennard, C. (2001). Impaired spatial working memory across saccades contributes to abnormal search in parietal neglect. *Brain*, 124, 941–952.
- Itti, L., & Koch, C. (2001). Computational modeling of visual attention. *Nature Reviews Neuroscience*, 2(3), 194–203.
- Kessen, W., Salapatek, P., & Haith, M. (1972). The visual response of the human newborn to linear contour. *Journal of Experimental Child Psychology*, 13, 9–20.
- Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, 4, 219–227.
- Mannan, S., Mort, D., Hodgson, T., Driver, J., Kennard, C., & Husain, M. (2005). Revisiting previously searched locations in visual neglect: Role of right parietal and frontal lesions in misjudging old locations as new. *Journal of Cognitive Neuroscience*, 17, 340–354.
- Maurer, D., & Salapatek, P. (1976). Developmental changes in the scanning of faces by young infants. *Child Development*, 47, 523–527.
- Norcia, A. M., Tyler, C. W., & Hamer, R. D. (1990). Development of contrast sensitivity in the human infant. *Vision Research*, 30, 1475–1486.
- Parton, A., Malhotra, P., Nachev, P., Ames, D., Ball, J., Chataway, J., et al. (2006). Space re-exploration in hemispatial neglect. *NeuroReport*, 17, 833–836.
- Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention & performance X* (pp. 531–556). Hillsdale, NJ: Erlbaum.
- Richards, J. E. (2001). Cortical indexes of saccade planning in infants. *Infancy*, 2, 123–133.
- Richards, J. E., & Holley, F. B. (1999). Infant attention and the development of smooth pursuit tracking. *Developmental Psychology*, 35, 856–867.
- Rumelhart, D. E., McClelland, J. L., & PDP Research Group (1986). *Parallel distributed processing: Explorations in the microstructure of cognition*. Cambridge, MA: The MIT Press.
- Salapatek, P., & Kessen, W. (1966). Visual scanning of triangles by the human newborn. *Journal of Experimental Child Psychology*, 66, 247–258.
- Sapir, A., Hayes, A., Henik, A., Danziger, S., & Rafal, R. (2004). Parietal lobe lesions disrupt saccadic remapping of inhibitory location tagging. *Journal of Cognitive Neuroscience*, 16, 503–509.
- Schiller, P. H. (1998). The neural control of visually guided eye movements. In J. E. Richards (Ed.), *Cognitive neuroscience of attention: A developmental perspective* (pp. 3–50). Mahwah, NJ: Lawrence Erlbaum Associates Inc.
- Simion, F., Valenza, E., Cassia, V., Turati, C., & Umiltà, C. (2002). Newborns' preference for up-down asymmetrical configurations. *Developmental Science*, 5(4), 427–434.
- Stein, J. F. (1989). Representation of egocentric space in the posterior parietal cortex. *Quarterly Journal of Experimental Physiology*, 74, 583–606.
- von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, 30, 369–382.
- Wentworth, N., & Haith, M. M. (1998). Infants' acquisition of spatiotemporal expectations. *Developmental Psychology*, 34, 247–257.
- Wojciulik, E., Husain, M., Clarke, K., & Driver, J. (2001). Spatial working memory deficit in unilateral neglect. *Neuropsychologia*, 39, 390–396.