Journal of Experimental Child Psychology 113 (2012) 177–185

Contents lists available at SciVerse ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Brief Report

Young infants' perception of the trajectories of two- and three-dimensional objects

Scott P. Johnson [a,*], J. Gavin Bremner [b], Alan M. Slater [c], Sarah M. Shuwairi [d], Uschi Mason [b], Jo Spring [b], Barrie Usherwood [b]

[a] *Department of Psychology, University of California, Los Angeles, CA 90095, USA*
[b] *Department of Psychology, Lancaster University, Lancaster LA1 4YF, UK*
[c] *School of Psychology, Exeter University, Exeter EX4 4QG, UK*
[d] *Department of Psychology, New York University, New York, NY 10003, USA*

ARTICLE INFO

Article history:
Received 23 December 2011
Revised 24 April 2012
Available online 15 June 2012

Keywords:
Infant perception
Depth perception
Visual development
Eye movements
Object knowledge

ABSTRACT

We investigated oculomotor anticipations in 4-month-old infants as they viewed center-occluded object trajectories. In two experiments, we examined performance in two-dimensional (2D) and three-dimensional (3D) dynamic occlusion displays and in an additional 3D condition with a smiley face as the moving target stimulus. Rates of anticipatory eye movements were not facilitated by 3D displays or by the (presumably) more salient smiley face relative to the 2D condition. However, latencies of anticipations were reduced, implying that 3D visual information may have supported formation of more robust mental representations of the moving object. Results are interpreted in a context of perceptual constraints on developing cognitive capacities during early infancy.
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Introduction

Over the past several decades, research on perceptual and cognitive development during infancy has flourished as a number of experimental paradigms based on infant looking behaviors have been developed to test learning and expectations of visual and auditory stimuli (Aslin, 2007). Much of this work concerns the developmental origins of knowledge of the physical world. Those with a nativist orientation (e.g., Baillargeon, 1993; Spelke, 1994) have claimed that infants reason about objects on the basis of innate core knowledge, including important principles such as persistence, solidity, and

* Corresponding author.
E-mail address: scott.johnson@ucla.edu (S.P. Johnson).

0022-0965/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jecp.2012.04.011

impenetrability of objects and basic rules governing their interactions with one another in space. Evidence comes chiefly from experiments that demonstrate early competence at object perception tasks. An alternative constructivist approach provides evidence for emergence of knowledge following important perceptual developments during the first year after birth (e.g., Johnson, 2010, 2011). Notably, task performance is susceptible to rather slight variations in stimulus parameters, and this can help to reveal processing constraints and their role in infants' analysis of objects and events. For instance, 4-month-old infants perceive an object that passes behind a screen as moving on a continuous path only when the gap in perception is spatially or temporally short (Bremner et al., 2005; Johnson et al., 2003b). Performance is facilitated by the addition of dynamic auditory information, which may support perception of a moving continuous object (Bremner, Slater, Johnson, Mason, & Spring, 2012a; Kirkham, Wagner, Swan, & Johnson, 2012) and is impeded when infants view displays that depict oblique trajectories through occlusion (Bremner, Slater, Mason, Spring, & Johnson, 2012b; Bremner et al., 2007).

The constructivist account emerging from this and related work suggests that perceptual processes underpin the later development of knowledge, and these perceptual processes themselves are subject to change during the first year. A potential critique of this conclusion, however, is that these object trajectory stimuli are computer generated and, therefore, do not constitute real objects; perceptual limitations revealed by this work concern infants' ability to process dynamic two-dimensional (2D) images and might not be so marked if three-dimensional (3D) displays were used (cf. Troseth, 2003; Troseth & DeLoache, 1998). It is possible, therefore, that differences in young infants' performance between 2D and 3D displays may have a crucial bearing on the debate between nativist and constructivist accounts.

Does 3D information enhance performance in object perception tasks? Evidence is mixed. On the one hand, young infants are sensitive to visual cues for 3D structure in 2D images (Kavsek, Yonas, & Granrud, 2012). For example, 3-month-olds detected orientation discrepancies in the depth plane when tested with 2D line drawings with a 3D interpretation (Bertin & Bhatt, 2006), and 4-month-olds discriminated between "possible" and "impossible" cubes in 2D images on the basis of line junctions and the local depth order of surfaces (Shuwairi, 2009; Shuwairi, Albert, & Johnson, 2007; Shuwairi & Johnson, 2012). Furthermore, Smith, Johnson, and Spelke (2003) showed that 4-month-olds' perception of the unity of misaligned, partly occluded surfaces was facilitated in a 3D condition relative to a 2D condition. Specifically, misaligned surfaces were perceived as disjoint in two dimensions but indeterminate in three dimensions, closer to an interpretation of an organized arrangement of objects in depth, perhaps because depth information was enhanced in the 3D condition. In addition, Mash and Bornstein (2012) found that visual exposure to 3D objects facilitated categorization in 5-month-olds, whereas exposure to 2D objects failed to have the same effect. On the other hand, several reports have revealed that young infants perceive aligned, center-occluded surfaces as unified in 2D displays (e.g., Johnson, 2004; Johnson and Náñez, 1995), implying that 3D information is not necessary to perceive objects as distinct and occupying discrete depth planes. Similarly, Jowkar-Baniani and Schmuckler (2011) reported that 9-month-olds detected the equivalence between line drawings of 3D objects (a doll and a sheep) and the objects themselves. It has been suggested, moreover, that young infants may respond to objects *more* effectively in impoverished 2D displays relative to richer 2D or 3D displays (Valenza, Leo, Gava, & Simion, 2006), perhaps because the immature visual system is unable to cope with an abundance of visual information.

Finally, studies of anticipatory tracking of 2D and 3D objects at 4 months of age also yield mixed results. Johnson and colleagues (Johnson, Amso, & Slemmer, 2003a; Johnson & Shuwairi, 2009) observed average rates of oculomotor anticipation (ROAs) on 20% to 27% of trials as infants viewed repetitive, center-occluded object trajectories in 2D displays and average rates of oculomotor reaction (RORs) on 43% to 49% of trials. ROAs in this condition were not reliably different from those in a control condition where the object moved on a random unpredictable trajectory ($M = 22\%$), implying that infants were not able to exploit the repetitive spatial and temporal event structure in determining the time and place of the object's emergence. However, using a 3D apparatus, von Hofsten, Kochukhova, and Rosander (2007) reported substantially higher ROAs in 4-month-olds, ranging from 36% to 63% (depending on occlusion duration and object speed) and an average ROR of 53% across conditions. Performance was improved significantly in Johnson and colleagues' studies (Johnson & Shuwairi, 2009;

Johnson et al., 2003a) by initial "training" with multiple exposures to fully visible trajectories (mean ROA = 36–40%, mean ROR = 38–43%). Training also effected reductions in latencies of both anticipatory and reactive eye movements. von Hofsten and colleagues (2007) did not report effects of training, but they did manipulate occlusion duration and noted that eye movement latencies appeared to be influenced by the time and place of object emergence, consistent with the hypothesis that infants maintained a representation of object movement that guided oculomotor planning.

On the face of it, it would appear that 3D displays were more effective in revealing evidence that 4-month-olds represent moving hidden objects and program eye movements to predict objects' appearance on the basis of these representations. Testing with real 3D stimuli, therefore, might be more conducive to young infants' latent capacity for representing hidden objects, in line with the nativist view. However, the methodology used does not necessarily allow a direct comparison to work using 2D displays. For example, infants in von Hofsten and colleagues' (2007) experiment sat inside a monochromatic cylindrical testing chamber. The occluder was the same color as the background, the moving object was an orange happy face, and infants were observed in multiple conditions that varied object speed and occluder size. In contrast, infants in Johnson and colleagues' experiments (Johnson & Shuwairi, 2009; Johnson et al., 2003a) viewed a large monitor depicting a green ball moving behind a blue rectangular occluder (Fig. 1A), both of which appeared against a textured background (white dots on black). Meanwhile, the ball traversed at a constant speed and the occluder size remained consistent across 48 identical trials. It is possible that these or other methodological differences led to variations in performance, and this question motivates experiments to directly compare infants' behavior in 2D and 3D testing conditions. Given the potentially crucial implications of a performance difference between 2D and 3D versions of the same tasks for the debate between nativist and constructivist accounts, the two experiments in the current study were designed to accomplish this goal.

We focused on 4 months as an age at which, according to nativist accounts, infants' abilities for representing hidden objects are well established (e.g., Aguiar & Baillargeon, 1999), whereas from a constructivist account this ability is still developing and, as such, is strongly susceptible to influence from stimulus characteristics. For example, as noted previously, 4-month-olds provide evidence of perception of trajectory continuity when the time or distance out of sight is brief, yet they respond as if a center-occluded trajectory consists of disconnected fragments of object movement if the spatiotemporal gap is extended only slightly (Bremner et al., 2007). Therefore, 4 months may represent an ideal age to explore questions of infants' responses to 2D versus 3D information.

Experiment 1

The aim of the first experiment was to provide a direct comparison of infant oculomotor performance when viewing 2D and 3D displays, each depicting a repetitive, center-occluded object trajectory. Data from a *3D condition* were compared with those from a *2D condition* described by Johnson and Shuwairi (2009). ROA and ROR data from the 2D condition were presented in the earlier report by Johnson and Shuwairi; latency data from the 2D condition were also collected by Johnson and Shuwairi and presented in the earlier report in aggregate form (i.e., averaged across anticipations and reactions). Latency data from the 2D condition broken up by anticipations versus reactions are provided here for the first time.

Method

Participants

The final sample in the 3D condition consisted of 16 4-month-olds (8 girls and 8 boys, mean age = 128.1 days, *SD* = 9.4). An additional 13 infants were observed but not included in the analyses due to fussiness (5), failure to calibrate the point of gaze (3), experimenter error (1), or excessive movement leading to data loss (4). The final sample in the 2D condition consisted of 12 4-month-olds (5 girls and 7 boys, mean age = 125.6 days, *SD* = 6.0). An additional 19 infants were observed but not included in the analyses due to fussiness (7), sleepiness (2), experimenter error (1), parental interference (3), or excessive movement leading to data loss (6). Each infant was required to contribute at

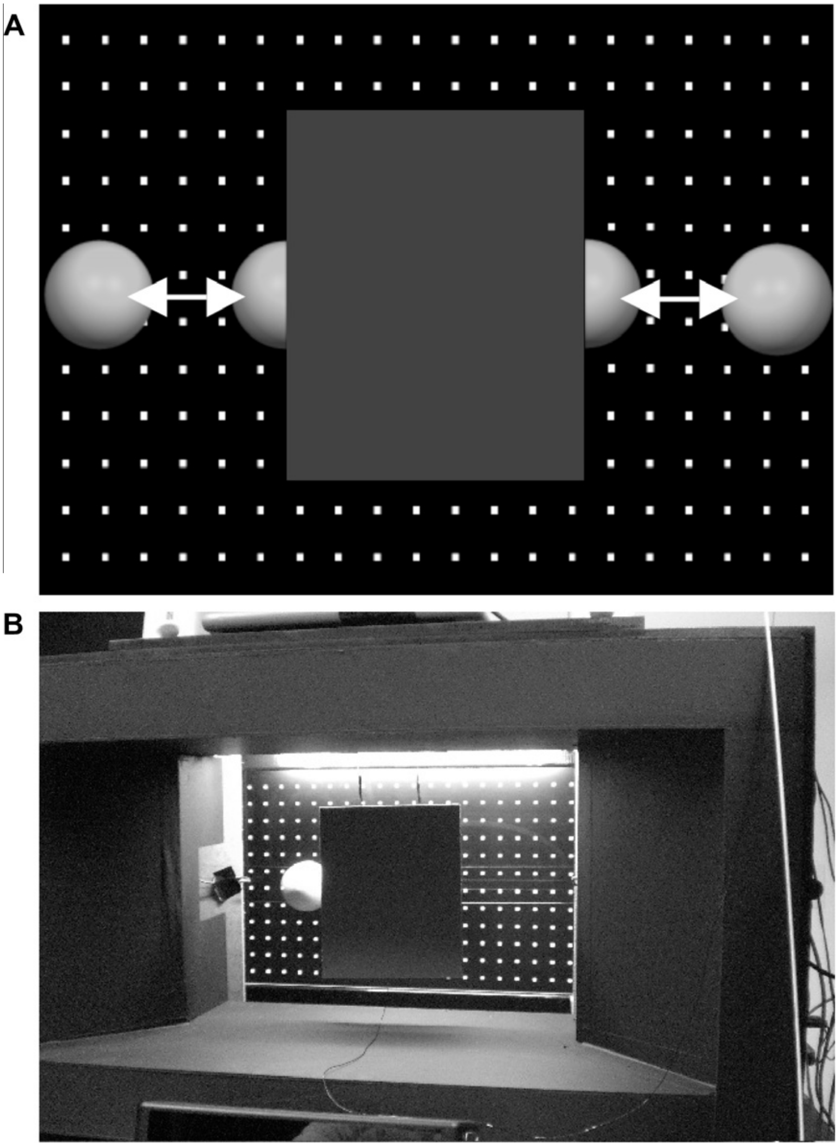

Fig. 1. (A) Schematic depiction of events shown to infants in the 2D condition. (B) Photograph of the apparatus used in the 3D and 3D Smiley conditions. The ball from the 3D condition is seen at the left. The supporting wires are shown here for illustrative purposes (illuminated by the camera flash) but were not visible under testing conditions.

least 50% of potential eye movement data points to be included in the final data set. All infants were full-term with no known developmental difficulties. Infants were selected from a public database of new parents and were recruited by letters and telephone calls.

Apparatus, stimuli, and procedure

In the 3D condition, infants were seated approximately 117 cm from a 58-cm Apple cinema display that enclosed the back of a stage apparatus (see Fig. 1B). Black cardboard framed a 20×12 grid of white dots against a black background (55.5×33.4 cm). A 21.5×17.7-cm ($11.9 \times 9.8°$ visual angle at infants' 103-cm viewing distance) blue occluder and a 6.7-cm (3.6°) green ball, 5 cm behind the occluder, were suspended in the stage area on fine wires that were inconspicuous to participants. The ball moved by means of a gear system attached to the wires, taking 2.5 s to travel from one side of the stage to the other, whereupon it changed direction and traveled back again, completing six cycles back and forth for each trial (12 traverses per trial, 8 trials, 96 traverses in total). Trials lasted 30 s each. The speed of the ball was 16.5 cm/s (9.4°/s). Eye movement data were recorded with a Tobii x60 eye tracker placed in front of and below the stimulus apparatus. Prior to testing, each infant's point of gaze was calibrated with the Tobii eye tracker's two-point calibration routine, an expanding and contracting target pattern presented in the top left and bottom right corners of the monitor. Calibration accuracy was verified by moving the pattern to random locations. Following calibration and before each trial, the occluder was lowered on its wires from the top of the stage. It was raised again after each trial, followed by an attention-getter presented on the center of the monitor for several seconds. A different nonrhythmic sound was played during each trial to maximize attention to the stimulus.

In the 2D condition, a Macintosh G4 computer and 76-cm Mitsubishi monitor were used to present stimuli. Each stimulus consisted of a 30-s animation depicting a 6.7-cm (3.8° visual angle at infants'

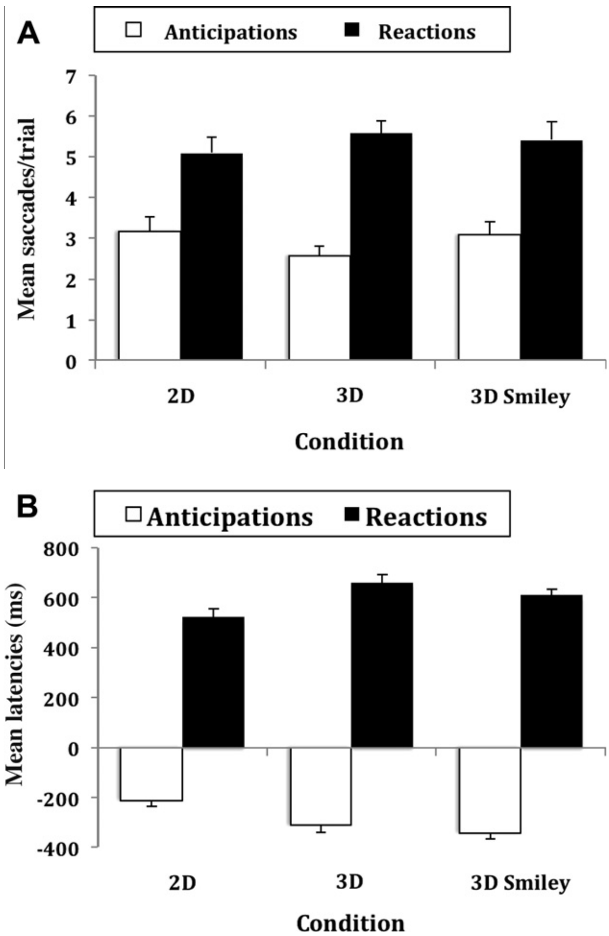

Fig. 2. (A) Saccade data from the 2D, 3D (Experiment 1), and 3D Smiley (Experiment 2) conditions (mean rates of anticipations and reactions per trial). (B) Latency data from the 2D, 3D (Experiment 1), and 3D Smiley (Experiment 2) conditions (mean latencies for anticipations and reactions in milliseconds). Negative numbers denote eye movements produced prior to the object's emergence; positive numbers denote eye movements produced in response to its emergence.

100-cm viewing distance) green ball translating laterally across 45.4 cm (25.5°) at 18.2 cm/s (10.4°/s), as depicted in Fig. 1A. The object changed direction (left–right) every 2.5 s. The center of the trajectory was occluded by a 21.5 × 17.7-cm (12.3 × 10.1°) blue box. Objects were presented against a textured background (a 20 × 12 grid of white dots on black) measuring 48.8 × 33.0 cm (27.4 × 18.7°). An Applied Science Laboratories (ASL) Model 504 eye tracking camera was placed on the table immediately in front of and below the stimulus monitor. As in the 3D condition, nonrhythmic sounds were played to maximize attention to the stimulus, every trial consisted of six complete cycles of the object trajectory, and there were 96 trials in total. Between trials, infants viewed a brief animation to recenter the point of gaze in both the 2D and 3D conditions. A two-point calibration routine was again used.

Data coding

We followed data coding protocols first described by Johnson and colleagues (Johnson & Shuwairi, 2009; Johnson et al., 2003a). Eye movements were coded from video records exported by Tobii Studio software (at 25 fps) or the ASL camera (at 30 fps) showing the point of gaze superimposed on the stimulus events for instances of "perceptual contact." In each passage of the object, an eye movement was entered into the data set if the point of gaze was directed toward a region of the display within 1.5° horizontally and 3.0° vertically of the moving object trajectory as it was visible on either side of the occluder after a starting position of the point of gaze outside this region. Trials in which the point of gaze did not leave this region were not counted, as when an infant remained fixated on one side of the display. To take account of the lag due to the time it takes to program an eye movement, eye movements leading to perceptual contact initiated 150 ms or less subsequent to object emergence were coded as anticipations, and those initiated later than 150 ms were coded as reactions. The 150-ms criterion was derived from past reports of predictive and reactive eye movements in infants (Canfield, Smith, Brezsnyak, & Snow, 1997) and adults (Fischer & Weber, 1993). Our dependent measures were (a) numbers of *saccades* (ROAs and RORs) per trial and (b) *latencies* of eye movements relative to object emergence.

Results and discussion

Saccades

Mean ROAs and RORs per trial from both experiments (see below for Experiment 2) are shown in Fig. 2A. Preliminary analyses incorporating sex and trial revealed no sex differences in performance or evidence of learning across trials, and the analyses reported here collapse across these variables. A 2 (Condition: 3D vs. 2D) × 2 (Saccade Type: anticipations vs. reactions) mixed analysis of variance (ANOVA) with repeated measures on the second factor revealed a statistically significant main effect of saccade type, $F(1, 26) = 63.16$, $p < .0001$, partial $\eta^2 = .71$, reflecting a greater number of reactions than anticipations overall, and no other reliable effects. Planned comparisons revealed no reliable differences between conditions in ROAs or RORs (*ps* > .15).

Latencies

Mean latencies of anticipations and reactions across trials from both experiments are shown in Fig. 2B. A Condition × Saccade Type mixed ANOVA revealed a statistically significant main effect of saccade type, $F(1, 26) = 666.42$, $p < .0001$, partial $\eta^2 = .96$, the result of faster latencies for anticipations than for reactions. There was also a reliable Condition × Saccade Type interaction, $F(1, 26) = 12.98$, $p < .01$, partial $\eta^2 = .33$. Simple effects tests revealed faster anticipations, yet slower reactions, by infants in the 3D condition ($p < .05$ and $p < .01$, respectively).[1]

[1] Recent tests of temporal accuracy of the Tobii T60XL eye tracker revealed inconsistencies in oculomotor latencies recorded by E-Prime software (used to present stimuli and store eye movements), Tobii Studio software, and an exported video record (Morgante, Zolfaghari, & Johnson, 2012). These errors may have stemmed in part from processing limits of Tobii Studio software during stimulus presentation, and they call for caution when interpreting latency data recorded on Tobii eye trackers. These concerns are mitigated in the current experiments for two reasons. First, Tobii Studio was not used to present stimuli. Second, a systematic bias in timing would presumably be reflected in either faster or slower latencies overall. Here we observed *both* patterns for different eye movement types (anticipations and reactions).

In summary, the saccade analyses revealed no benefit from 3D information to performance, evidence for which would come from a greater number of anticipations in the 3D condition. However, anticipatory eye movements in the 3D condition were reliably faster even as reactions were slower, implying that 3D information may have conferred an advantage at some level. We return to this issue in the General Discussion.

Experiment 2

The aim of the second experiment was to examine the possibility that 4-month-olds' performance in von Hofsten and colleagues' (2007) study—substantially higher ROAs relative to experiments reported by Johnson and colleagues (2003b) and Johnson and Shuwairi (2009)—may have stemmed from the use of a (presumably) highly salient and interesting moving object, namely a happy face. This hypothesis was tested with a *3D Smiley* condition—a replication of the 3D condition reported in Experiment 1 using a happy face painted on the moving spherical object.

Method

Participants

The final sample in the 3D Smiley condition consisted of 16 4-month-olds (7 girls and 9 boys, mean age = 127.7 days, *SD* = 9.2). An additional 10 infants were observed but not included in the analyses due to fussiness (4), failure to calibrate the point of gaze (2), or excessive movement leading to data loss (4).

Apparatus, stimuli, procedure, and data coding

The protocols of Experiment 2 were identical to those described for Experiment 1 except that a smiley face was painted on the moving green ball in black paint.

Results and discussion

Saccades

A Condition (3D vs. 3D Smiley) × Saccade Type mixed ANOVA revealed a statistically significant main effect of saccade type $F(1, 30) = 51.93$, $p < .0001$, partial $\eta^2 = .63$, reflecting a greater number of reactions versus anticipations overall, and no other reliable effects. Planned comparisons revealed no reliable differences between conditions in ROAs or RORs ($ps > .15$). A comparison of the 2D and 3D Smiley conditions yielded outcomes similar to those reported in Experiment 1—no reliable differences in ROAs or RORs as a function of condition ($ps > .59$).

Latencies

A Condition × Saccade Type mixed ANOVA yielded a significant main effect of saccade type, $F(1, 30) = 308.19$, $p < .0001$, partial $\eta^2 = .91$, the result of faster latencies for anticipations than for reactions, and no other reliable effects (see Fig. 2B). Planned comparisons revealed no reliable differences between conditions in latencies for anticipations or reactions ($ps > .15$). A comparison of the 2D and 3D Smiley conditions also yielded outcomes similar to those of Experiment 1—a reliable main effect of saccade type and a reliable Condition × Saccade Type interaction. As in the first experiment, the interaction arose from a combination of faster anticipations and slower reactions by infants in the 3D Smiley condition ($ps < .05$).

In summary, analyses of saccades and latencies revealed no reliable differences in performance between the 3D and 3D Smiley conditions, implying that attempts to increase the salience of and attention to the moving object (in line with the methods of von Hofsten et al., 2007) did not have the hypothesized effect.

General discussion

We compared 4-month-olds' responses to moving 2D and 3D objects emerging from and passing behind a stationary occluder. Despite the repetitive and predictable nature of such events, young infants' perception of trajectory continuity is rather tenuous and susceptible to a number of subtle variations of display parameters (Bremner et al., 2007, 2012b). Responses of older infants, in contrast, are more robust (Johnson et al., 2003a, 2003b). The goal of the current experiments was to compare performance in 2D and 3D versions of the paradigm directly, and we found that 3D displays elicited a combination of faster predictive and slower reactive eye movements relative to 2D stimuli. At the same time, the rates of anticipation and reaction did not differ reliably between conditions. Therefore, presentation of stimuli in three dimensions did not have a dramatic effect on performance, as predicted on a nativist account, but instead yielded more subtle variations in behavior, consistent with a constructivist account stressing the context-dependent nature of infants' responses to occlusion events.

Nevetheless, one proposal that may account for these results is the possibility that 3D information heightens infants' engagement in the task of following the moving object as it becomes hidden. The object is tracked by recourse to a mental representation of its motion trajectory, and this representation (and its effect on programming oculomotor anticipations) may be facilitated by the use of real objects in a 3D environment that presents binocular disparity, shading, shadows, reflections, highlights, and other information that is absent in 2D stimuli. A deeper engagement in predictive behavior may have the complementary effect of inhibiting reactions to some extent, an effect observed in both the 3D and 3D Smiley conditions. That is, if infants are occupied by following a "mental image" of a moving hidden object, they may require additional time to disengage from this process and respond to the object's appearance on the other side of the occluder. However, ROAs, an important dependent measure in common use across studies of infants' object tracking (see Gredebäck, Johnson, & von Hofsten, 2010, for a review) did not show a benefit from 3D displays. Moreover, analyses from one-way ANOVA on proportions of trials yielding valid data showed no reliable differences across conditions (*M*s = 68.8, 70.0, and 70.2% for 2D, 3D, and 3D Smiley conditions, respectively, $p > .90$). Even so, testing conditions reported here and by Johnson and colleagues (Johnson & Shuwairi, 2009; Johnson et al., 2003a) may have led to more distractibility than those used by von Hofsten and colleagues (2007), and performance may be facilitated with less visual clutter to compete for infants' attention. Specifically, greater attention to the moving ball (as opposed to its surroundings) may have reduced cognitive demands posed by processing other elements in the scene and led to strengthened object representations when the ball was hidden from view, in turn facilitating ROAs.

A final related issue is the challenge in gauging infants' "true" cognitive capacity. Are ROAs a reliable and valid index of object representations? Even in the most conducive circumstances reported to date—von Hofsten and colleagues' (2007) study—ROAs in 4-month-olds are not very consistent (less than half of eye movements) but instead remain susceptible to perceptual constraints such as time and distance out of sight. The "distractible" conditions used in the current study are in some ways more representative of the "real-world" visual environment, which is far richer in information content than many laboratory settings, including that of von Hofsten and colleagues. Thus, our conditions are arguably better structured to measure perceptual capacity in real-world settings. Our results are consistent with the hypothesis that infants' cognitive operations are strongly influenced by perceptual limitations that are liable to constrain infants' ability to interpret the rich perceptual world they encounter. At the same time, comparison of our results with those from other labs helps to reveal the conditions under which these emerging capacities become more robust with development.

Acknowledgments

This work was supported by Economic and Social Research Council (ESRC) Grant R000239979 and National Institutes of Health (NIH) Grant R01-HD40432. The authors acknowledge the assistance of staff at University Hospitals of Morecambe Bay NHS Trust in recruitment and are grateful to parents and infants who took part in the work.

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