

Play enhances visual form perception in infancy—an active training study

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Funding information

Riksbankens Jubileumsfond, Grant/Award
Number: P15-0430:1

Abstract

Motor experiences and active exploration during early childhood may affect individual differences in a wide range of perceptual and cognitive abilities. In the current study, we suggest that active exploration of objects facilitates the ability to process object forms and magnitudes, which in turn impacts the development of numerosity perception. We tested our hypothesis by conducting a preregistered active exploration intervention with 59 8-month-old infants. The minimal intervention consisted of actively playing with and exploring blocks once a day for 8 weeks. In order to control for possible training effects on attention, we used book reading as a control condition. Pre- and post-test assessments using eye-tracking showed that block play improved visual form perception, where infants became better at detecting a deviant shape. Furthermore, using three control tasks, we showed that the intervention specifically improved infants' ability to process visual forms and the effect could not be explained by a domain general improvement in attention or visual perception. We found that the intervention did not improve numerosity perception and suggest that because of the sequential nature of our hypothesis, a longer time frame might be needed to see improvements in this ability. Our findings indicate that if infants are given more opportunities for play and exploration, it will have positive effects on their visual form perception, which in turn could help their understanding of geometrical concepts.

KEYWORDS

approximate number system, embodiment, visual form perception

1 | INTRODUCTION

The idea that early motor experiences help shape cognitive development has a long history in psychology (Piaget, 1964). More recent research on embodied cognition provides support for this idea. Our motor system plays a role in the development of perception and cognition (Campos et al., 2000; Lakoff & Núñez, 2000; Libertus, Joh, & Needham, 2016), especially early in life. Some of the work supporting this idea has been correlational. For example, the onset of walking and standing in infancy correlates with executive functions in adulthood (Ridler et al., 2006) and further, 18-month-olds' motor

skill correlate with both inhibition and working memory (Gottwald, Achermann, Marciszko, Lindskog, & Gredebäck, 2016). Motor ability has, in a similar manner, been associated with changes in attention/priming (Gredebäck & Daum, 2015), encoding (Woodward, 2013) and prediction (Gredebäck & Falck-Ytter, 2015) of other people's action goals.

Studies that actively train motor abilities and measure the resulting effect on perception and cognition are fewer and, in most cases, rely on a paradigm known as 'sticky mittens'. In these interventions, 3 to 4-month-old infants, who do not yet have the ability to successfully reach for and grasp objects, are given mittens that allow them

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to pick up velcro-covered objects (Needham, Barrett, & Peterman, 2002). Positive effects of sticky mittens training have been found on: grasping (Libertus & Landa, 2014), object processing and exploration (Libertus et al., 2016; Needham et al., 2002; Wiesen, Watkins, & Needham, 2016; Williams, Corbetta, & Guan, 2015), causality perception (Rakison & Krogh, 2012), teleological processes (Skerry, Carey, & Spelke, 2013) and sensitivity to goal-directed actions (Bakker, Sommerville, & Gredebäck, 2015; Gerson & Woodward, 2014). Together these findings demonstrate that individual differences in a wide range of perceptual and cognitive abilities can be affected by motor experiences and active exploration during early childhood.

In this paper, we suggest that active exploration of objects facilitate the ability to process object forms and magnitude properties, such as size, weight and numerosities. More specifically, motor-based active exploration should serve as a training ground for the perception system, allowing for better and more in-depth processing of visual forms and magnitudes. We suggest that this process should operate in a sequential manner where active motor experiences will first facilitate the development of visual form perception, and visual form perception should in turn impact the development of magnitude perception. Before elaborating more on this hypothesis we need to look at each of the perceptual processes involved, starting with visual form perception.

The previous literature has identified at least two distinct types of situations in which people need to represent spatial information (Spelke, Lee, & Izard, 2010). First, when navigating in our surroundings we need to represent the shape and spatial layout of large surfaces (Spelke et al., 2010). For example, if we exit a subway station and become disoriented we can reorient ourselves by noticing the distances and directional relations between landmarks. The second type of situations, more relevant to the current study, has to do with recognizing and categorizing smaller objects based on shape, which is important for determining the function and affordances of objects (Spelke et al., 2010). For example, determining if an object can be used as a tool for a specific goal requires sensitivity to that object's shape. Here we will refer to the perceptual process relevant in the second set of situations as visual form perception. This encompasses encoding angles, relative lengths and sense (or directions) of smaller objects and 2D shapes (Spelke et al., 2010).

Infants are sensitive to object shape from an early age (Izard & Spelke, 2009; Schwartz & Day, 1979; Slater, Mattock, Brown, & Bremner, 1991; Younger & Cohen, 1983). Slater et al. (1991), for example, showed that already 3 days after birth, infants are able to encode the angle of 2D forms. More recently, studies using eye tracking have shown that infants can make similar discriminative judgments, with respect to geometric properties of small forms, as children and adults (Lindskog, Rogell, Kenward, & Gredebäck, 2019). Visual form perception is also thought to become more sensitive with age, with sensitivity to certain properties developing faster than others (Izard & Spelke, 2009). For example, children's sensitivity to length develops faster than their sensitivity to angles and their ability to detect mirror images is the slowest to develop (Izard & Spelke, 2009).

Research Highlights

- We conducted a training study where 8-month-old infants actively played with blocks together with their caregivers.
- Compared to an active control condition, block playing enhanced infants' ability to detect a deviant shape, conceptualized here as visual form perception.
- Enhanced visual form perception could not be explained by a domain general increase in attention or visual perception.

More generally, there are stable individual differences in the ability to represent spatial information in both children (Lauer & Lourenco, 2016; Verdine et al., 2014) and adults (Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017). This has attracted attention from researchers as visual form perception is thought to play a key role in the development of geometrical concepts (Izard & Spelke, 2009). Educators and policy-makers have also emphasized the importance of these skills, partly because individual differences in spatial perception and reasoning can predict success in STEM (Science, technology, engineering and mathematics)-related disciplines (Verdine et al., 2017). However, it is unclear what drives the individual differences in spatial ability. Some studies indicate that factors such as block building, puzzle solving and exposure to spatial language may influence the spatial abilities in preschoolers (Verdine et al., 2017). However, individual differences in spatial sensitivity may already be present in infancy, before children can engage in such activities. Lauer and Lourenco (2016) found that sensitivity to spatial information between 6 and 13 months of age predicted mental-transformation skill and understanding of formal math concepts at 4 years of age. Although infants cannot engage in complex tasks like puzzle solving, it is possible that simpler types of motor experiences can drive these early differences in spatial sensitivity.

The idea that motor experiences affect spatial processing is not new and there is correlational support for the idea. Frick and Möhring (2013), for example, found that 10-month-olds' motor development correlated with their mental rotation ability. Furthermore, Soska, Adolph, and Johnson (2010) showed that sitting experience, which facilitates efficient reaching, and visual-manual exploration skill correlated with 3D object completion in 4.5- to 7.5-month-olds. There is also tentative evidence for a causal relationship between motor experiences and spatial processing in infants. For example, it has been found that hands-on experience with objects affects infants' ability to mentally rotate those objects. Möhring and Frick (2013) showed that 6-month-olds who were allowed to manually explore objects performed better on a subsequent test of mental rotation, compared to infants who had only visually observed the objects before the mental rotation test. Similarly, Slone, Moore, and Johnson (2018) showed that 4-month-olds who were allowed to explore objects using sticky mittens were better able to mentally rotate similar

objects shown on a screen, directly after the sticky mittens experience. Taken together, these findings provide strong support for a link between early motor experiences and spatial sensitivity. However, because these studies (Möhring & Frick, 2013; Slone et al., 2018) used similar objects during exploration and test, and tested spatial sensitivity immediately after exploration, it is unclear if such motor experiences would affect object or spatial processing that is not directly related to the motor experience, or if motor experiences would have long-lasting effects, capable of affecting individual differences. We therefore need more evidence before we can claim that early motor experiences drive individual differences in spatial sensitivity.

We suggest that with an enhanced ability to process visual forms, infants gain access to new and enhanced information about shapes, angles and size that might help them develop other capacities that rely on the processing of magnitude information. One candidate system that could be affected is the approximate number system (ANS), which allows infants to represent the numerosity of sets in an approximate, non-symbolic way (Izard, Sann, Spelke, & Streri, 2009; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). It might enable infants to, for example, compare which of two boxes has the most toys or keep track of how many people are in a group and notice if some leave the group. Although functional throughout development, the acuity of the ANS improves with age (Halberda & Feigenson, 2008; Izard et al., 2009; Xu & Spelke, 2000) and varies between individuals, both in children and adults, and this individual variation is thought to be important partly because it correlates with math achievement (Feigenson, Libertus, & Halberda, 2013; Halberda & Feigenson, 2008; Halberda, Mazocco, & Feigenson, 2008; Libertus & Brannon, 2010). The most common theoretical interpretation is that the ANS is an encapsulated and specialized system, dedicated to processing numerosities (core knowledge perspective; Carey, 2009; Feigenson, Dehaene, & Spelke, 2004; Izard et al., 2009; Xu & Spelke, 2000). However, an alternative theoretical account suggests that infants instead possess a more generalized magnitude system that processes not only numerosities but also magnitudes such as size, duration and spatial extent (Bulf, Hevia, & Cassia, 2016; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Walsh, 2015) and that specialization into separate systems develops over time as result of motor experiences (Walsh, 2015). To our knowledge, no published study has explicitly tested the relation between visual form perception and ANS acuity in infancy. There is however a large literature showing that spatial abilities in general are related to formal mathematics achievement later in life (Cheng & Mix, 2014; Frick & Möhring, 2016; Lauer & Lourenco, 2016; Verdine et al., 2017), but if this relation can in part be explained by visual form perception affecting ANS acuity is not yet known.

1.1 | The active exploration hypothesis

Based on the idea that differences in early motor experiences can impact visual form perception, we formulate a novel hypothesis, the active exploration hypothesis which has two parts. The first part states that motor-dependent exploration of the environment

during infancy gives rise to experiences that increase sensitivity to the shape of objects (visual form perception). The second part of the hypothesis states that this increased visual form sensitivity in turn leads to better ANS acuity.

As infants gain the ability to reach for and manipulate objects, they are able to process richer information about those objects than when simply looking at them. They are able to rotate objects and transfer them between hands and examine them from different perspectives. Efficient reaching and handling also gives rise to richer multimodal exploration, like being able to see and feel, both with the hands and mouth, the different sides of an object. These types of motor experiences increase attention to properties that are important for successful interactions with objects, such as the shape and size of objects. Infants thereby, over time, become better at processing object features, seen as improved visual form perception.

When infants become more sensitive to visual forms, they also process more magnitude information, such as the size of an object's angles, the length of its sides, the extent of its surfaces and the weight of the object. Infants' magnitude processing also becomes richer in that they can experience these magnitudes multimodally and observe that object properties and magnitudes remain invariant over transformations in space. As magnitude processing is strongly related to numerosity processing (Bulf et al., 2016; de Hevia et al., 2014; Walsh, 2015), the increase in rich magnitude input is thought to gradually strengthen the infants' ability to perceive numerosities. We hypothesize that this results in a fine-tuning of infants' ANS acuity.

1.2 | The current study

The overarching aim of the current study was to empirically test our active exploration hypothesis' two steps by conducting an active intervention with 8-month-old infants. Our first goal was to increase the amount of motor-dependent exploration that infants engage in and test if this leads to increased visual form perception. Secondly, if improvements in visual form perception are found, does this lead to improvements in ANS acuity? We conducted an OSF preregistered training study (https://osf.io/qapf4/?view_only=08e4558fad6b4043b5572c919a5d20ee) using a novel intervention consisting of actively playing with blocks. We used an active control group where parents read age-appropriate books to their infants in order to control for the possibility that our intervention improved infants' sustained attention. Previous work has shown that dialogic reading promotes vocabulary growth (Vally, Murray, Tomlinson, & Cooper, 2015), but there are no studies indicating that book reading should affect motor skills, visual form perception, or ANS acuity.

We tested two specific predictions made by the active exploration hypothesis. After the intervention, infants in the experimental group should perform better than infants in the control group on both (a) a visual perception task and (b) an ANS acuity task, and neither of these improvements should be explained by a general increase in attention. Further, we explored the specificity of possible effects on visual perception and ANS acuity by assessing visual

search performance and performance on an approximate addition task respectively. We also tested the two more general predictions that the intervention should result in (c) higher levels of object exploration in the experimental group as compared to the control group and that (d) the intervention should not affect the performance on an unrelated eye-tracking task, targeting another form of numerical information processing (perception of probabilities) (Kayhan, Gredebäck, & Lindskog, 2018).

2 | METHOD

2.1 | Participants

We recruited 59 (32 girls) 8-month-old infants (Mean age = 245 days, $SD = 9.4$, range 229–263) by contacting families who had previously expressed interest in participating in studies. We chose to test 8-month-olds because we reasoned that at this age, block play would be a motivating and interesting for infants, but not be an activity that they regularly engage in. We aimed for a sample size of 60 but did not achieve this due to a late cancellation. Thirty infants were randomly allocated to the block-training group and 29 to the book group. Between pre- and post-test one family from the block-training group dropped out, resulting in 58 infants participating in the post-test assessment 8 weeks later (Mean age = 308 days, $SD = 9.5$, range 289–330). Families received gift vouchers worth approximately €30 for their participation. Caregivers gave their written informed consent prior to each laboratory visit. Caregivers were on average 36 years old (range 21–56) and 82.2% had a University education. The vast majority of caregivers were born in Sweden.

2.2 | Design

The study used a 2×2 mixed design with training group (blocks or reading) as the between-subject factor and time (pretest and post-test) as the within-subject factor. Caregivers were blind to the exact hypotheses of the study and were told that we were interested in the effect of block play or book reading on general cognitive development. Also, caregivers were unaware of the other training group. These steps were taken to make sure that caregivers would not influence their infant by changing their behaviour in ways other than engaging in the training procedure. After the post-test, caregivers were debriefed as to the exact nature of the study. The study was approved by the regional ethics committee (EPN; reference number: 2016/362).

2.3 | Procedure and materials

2.3.1 | Pretest

Caregivers and infants visited the laboratory for a pretest assessment that lasted approximately 45 min. Infants completed

eye-tracking tasks, divided over two blocks, and two behavioural assessments in-between eye-tracking blocks. Each eye-tracking block lasted approximately 8 min and the behavioural assessments took around 10 min. By eye tracking, we assessed our main variables of interest; visual form perception and ANS acuity. We also used eye tracking to assess our supplementary tasks – probability perception, visual search and approximate addition. The behavioural assessments consisted of a manual exploration task and a visual attention task. Caregivers also answered questions about demographic information. After the pretest assessment, caregivers received information and materials needed for the home training. Furthermore, as part of two student projects, caregivers also answered the following questionnaires: Infant Behaviour Questionnaire (Putnam & Rothbart, 2006), Colorado Child Temperament Inventory (Rowe & Plomin, 1977), Vineland II, and the Confusion, Hubbub, and Order Scale (Matheny, Wachs, Ludwig, & Phillips, 1995). These questionnaires will not be reported on here.

2.3.2 | Training

We instructed caregivers to play with blocks or read books for 5 min a day, 5 times a week during the following 8 weeks. We gave caregivers a logbook and asked them to make a note every time they completed a training session. They did not, however, enter the length of each training session. Caregivers in both groups were instructed to be enthusiastic during the sessions and to encourage the child to actively participate in the activity. We also asked that they only use the materials during the training sessions. Furthermore, we gave both groups eight different 'exercises' (more information below) that consisted of different ways of performing the activities and asked caregivers to vary between these exercises. We asked caregivers to film their second training session and one session after 4 weeks and send to the laboratory, this was done to motivate caregivers.

Block-training group

Caregivers and infants in the block group received a box with 19 wooden blocks of different colours. Each box contained cubes, cylinders, cuboids of different lengths and widths, arcs and triangular prisms. Caregivers were also given written descriptions and pictures of eight different exercises. The exercises included: building tall towers, building wide towers, building two towers next to each other, knocking towers down, building structures using the same colour, banging blocks together, putting blocks in the box and building an archway and passing blocks through the arch. We reasoned that these activities would encourage infants to manually explore the blocks. The experimenter demonstrated a few of the exercises while playing with the child in order to model the type of active play that we were after. Furthermore, caregivers were instructed to let the child reach for, feel and explore the blocks with their mouth, thereby actively participating in the activity. Previous studies have looked at

the effect of block play in older children, but those studies are very different in that they focus on construction rather than exploration (Casey et al., 2008; Schmitt, Korucu, Napoli, Bryant, & Purpura, 2018; Verdine et al., 2014).

Book group

Caregivers and infants in the book group received two age-appropriate books. One of them was a story book with colourful pictures and one sentence per page and the other book had pictures with labels of different objects and animals. Caregivers were given written descriptions and pictures of eight different exercises. The exercises included focusing on colours, animals, sounds that objects or animals make, clothing, finding the main character in the story book, focusing on activities and finding the character's parents. Participants were instructed to let the child actively participate by, for example, pointing to things in the book together. Book reading was chosen as a control condition because we reasoned that it would afford infants with similar opportunities to practice sustained attention together with their caregiver as the block playing activity.

2.3.3 | Post-test

After 8 weeks, caregivers and infants visited the laboratory for a post-test assessment that was identical to the pretest.

2.4 | Stimuli and apparatus

2.4.1 | Eye-tracking apparatus

Infants gaze was measured using a Tobii TX300 Eye Tracker (Tobii Technology AB, www.tobii.com), which records the reflection of near infra-red light in the pupils and corneas of both eyes at 60 Hz (precision = 0.5°, spatial resolution < 0.3°). Infants were seated in their caregiver's lap, approximately 60 cm from the screen. Prior to each of the two eye-tracking blocks, a standard 5-point calibration (Gredebäck, Johnson, & Von Hofsten, 2010) was conducted and caregivers were instructed not to point, comment or influence their child in any way.

2.4.2 | Main tasks

Visual form perception

The task was adapted from Lindskog et al. (2019). On each trial, infants were presented with an array of four forms, each consisting of two connected lines (5.9 visual degrees long) forming an angle (see Figure 1). The forms were arranged in a square pattern with each form placed in one of the quadrants. The orientation of each form was different. The entire array subtended 27×19 visual degrees, with each individual form subtending 12×8 visual degrees. Each array included three forms that were identical (distractor forms) in

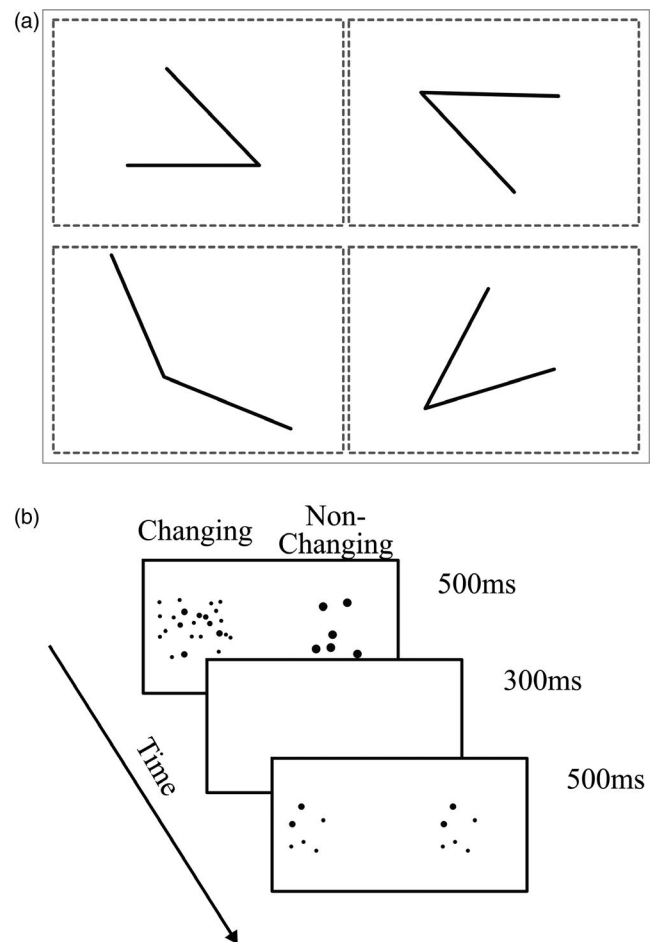


FIGURE 1 Main tasks. Examples of the visual form perception (a) and approximate number system (ANS) acuity (b) tasks. In the visual form task, infants are presented with four forms, three which have the same angle (distractors) and one which deviates in angle (target). Note that the dotted line around each form represents the AOIs and were not presented during the task. In the ANS acuity task, infants are presented with two image streams, one numerically constant stream which always presents the same number of dots, and one numerically changing stream which alternates between showing two numerosities

terms of geometrical properties (angle, length, and/or enclosed area) while the fourth form (target form) deviated. The degree to which the target form deviated was manipulated in terms of difference in angle size to two levels. In the 60° condition, the target form had an angle that was either 60° smaller or 60° larger than the base-line forms (120° vs. 60°). In the 90° condition, the corresponding difference was 90° (135° vs. 45°). Infants were presented with four 60° deviation trials and four 90° deviation trials. A trial lasted 5 s and we required infants to have fixated the screen 25% of the trial for it to be valid. We measured infants' looking time to each of the four forms and calculated their preference for the target form as:

$$DV_{VF} = \frac{LT_{\text{target form}}}{(LT_{\text{target form}} + \sum LT_{\text{distractor form } i})}$$

where $LT_{\text{target form}}$ and $LT_{\text{distractor form } i}$ is the looking time to the target form and i :th distractor form, respectively.

ANS acuity

We measured infants' numerosity perception using a version of Libertus and Brannon's (2010) numerical change detection task, adapted to be suitable for eye tracking on a single screen and repeated measurements. On each trial, infants are shown two streams of images, one on the right side and one on the left side of the screen. The images consist of black dots presented on a white background (see Figure 1). Each image was presented for 500 ms with 300 ms blank screen between images and a trial lasted 10 s. In the numerically changing image stream, the number of dots alternated between two numerosities on consecutive images. In the non-changing stream, the same number of dots was always presented. For example, the changing stream could alternate between showing 10 and 20 dots while the non-changing stream would always show 10 dots. The dots varied randomly in size (diameter ranging between 0.4 to 1.25 visual degrees) and the dots in each stream were presented in a 10×10 visual degree area. The distance between the centres of the streams was 24 visual degrees. To be sure that the infants did not use clues other than numerical magnitude, the average size of the dots was equated between the two streams on half of all images while the other half equated the cumulative area of the dots in each stream. The difficulty of the task was manipulated by the ratio between the two numerosities shown in the changing stream. Infants were shown nine trials, three with a 1:4 ratio (easy trials), three with a 1:2 ratio (medium trials) and three with a 2:3 ratio (hard trials). The side of the changing stream was counterbalanced across trials. We analysed infants' looking time to the changing and non-changing stream. We required infants' to have looked at each stream for at least 200 ms in order for the trial to be valid. For every valid trial, we calculated infants' preference for the changing stream as:

$$DV_{ANS} = LT_{\text{changing stream}} / (LT_{\text{changing stream}} + LT_{\text{non - changing stream}})$$

Manual exploration task

The task was adapted from Libertus et al. (2016), although they used the task to test older infants (15-month-olds). Infants were seated at a table in a high chair. We placed a complex toy that was attached to the table with a string in front of the infant. Infants were left to play with the toy for 5 min while the experimenter and caregiver busied themselves with questionnaires. The session was video recorded and later coded for active exploration. We counted the number of seconds infants spent simultaneously looking and touching the toy and used this as the dependent variable. The highest possible score would therefore be 300 s. We double-coded 10% of the recorded sessions, and inter-coder-reliability was excellent ($r = .983$).

Visual attention task

The task was based on a procedure used by Cuevas and Bell (2014) measuring visual attention in 5-month-old's. During the task, infants were seated in a high chair by a table and the caregiver was seated behind, out of the infant's view. The experimenter sat across from the infant with a hand-puppet and a trial started by the experimenter knocking on the table with the puppet three times. The experimenter

then lifted the puppet up to shoulder height and gently waved with the puppet's hands and head. The trial ended when the experimenter determined that the infant had looked away from the puppet for three consecutive seconds. A new trial was then started by the experimenter lowering the puppet and knocking three times on the table to grab the infant's attention. Infants were presented with four trials and the session was video recorded. We coded how long each trial lasted, that is, how much time passed before the infant looked away from the puppet for three consecutive seconds. Based on Cuevas and Bell (2014), the dependent variable was defined as the duration of the infant's longest trial. We double-coded 10% of all trials and inter-coder-reliability was excellent ($r = .922$).

2.4.3 | Supplementary tasks-probability perception, visual search and approximate addition

We assessed infants' probability perception using an eye-tracking task developed by Kayhan et al. (2018) that measures difference in looking time to likely and unlikely samples (see Supporting Information for full details). Furthermore, we assessed visual search performance by presenting infants with pictures of targets embedded among distractors (0, 3, 6 or 9 distractors) and measured latency to fixate the target (see Supporting Information for full details). Finally, we presented an approximate addition task where infants are shown addition events where the outcome of the addition is either expected or unexpected (i.e. $5 + 5 = 10$ or 5) (see Supporting Information for full details).

2.4.4 | Data analysis

All eye-tracking data were exported as raw data and imported into TimeStudio (Version 3.18, Nyström, Falck-Ytter, & Gredebäck, 2016; www.timestudioproject.com), an open source analysis environment running in MATLAB (R2014B). Data and settings for the eye-tracking data analyses can be downloaded via OSF (https://osf.io/qapf4/?view_only=08e4558fad6b4043b5572c919a5d20ee). All analyses were specified in the preregistration and we used an intention-to-treat plan where all infants who returned for post-test assessment were included in the analyses, regardless of how many training sessions they had completed.

Statistical analyses were carried out in RStudio (RStudio-Team, 2015) (version 1.1.453). Because infants do not always complete all trials and there may be problems with sphericity in the dataset, we decided to evaluate our hypotheses using general linear mixed models (GLMM) instead of the more common repeated measures analyses of variance. GLMMs were fitted using the *lme4* package in RStudio and effects were evaluated using likelihood tests. For the main eye-tracking tasks (visual form perception and ANS acuity), participant and trial number were set as random factors and condition (block or book reading) and time point (pretest or post-test) as fixed factors. In the GLMM for visual form perception, angle (60- or 90° deviation) was

set as a fixed factor and in the GLMM for ANS acuity, ratio (1:4, 1:2 or 2:3) was also set as a fixed factor. For the behavioural tasks (manual exploration and visual attention), participant was set as a random factor and time point as a fixed factor. The supplementary tasks were also analysed using GLMMs, details of which can be found in the Supporting Information. For all eye-tracking tasks, two participants were excluded because of very poor calibrations (determined visually using gaze-replay).

3 | RESULTS

3.1 | Intervention compliance

Caregivers were instructed to play or read with their infant five times a week for 8 weeks (40 sessions in total) and to note down every session in a logbook. Analysis of logbooks showed that caregivers and infants completed on average 39.3 sessions ($SD = 6.20$, $min = 23$, $max = 56$) in the block-training group and 39.1 sessions ($SD = 4.92$, $min = 22$, $max = 50$) in the book group. With a session length of 5 min, this is equivalent to a total of 196.5 and 195.5 min of play in the block and book groups respectively. The difference in completed sessions was not significant ($t_{56} = 0.117$, $p = .907$).

3.2 | Effect of intervention on visual form perception

The descriptive statistics for the visual form sensitivity task can be seen in Table 1. We first predicted that the block-training group should perform better on the visual form task after the training intervention compared to the book group. We tested this prediction by submitting the proportion score to a GLMM and the resulting model revealed two significant effects: the condition by time point interaction ($\chi^2(1) = 4.912$, $p = .027$) and the main effect of angle ($\chi^2(1) = 10.1$, $p < .002$). All other effects were non-significant (all $ps > .18$).

The main effect of angle indicates that infants across groups and time points looked more to the target form on the 60° trials ($M = 0.410$, $SD = 0.109$) compared to the 90° trials ($M = 0.336$, $SD = 0.109$). The interaction between condition and time point is illustrated in Figure 2. At pretest, the book group did not perform better, on the visual form task ($M = 0.392$, $SD = 0.101$) compared to the block group ($M = 0.331$, $SD = 0.167$). However, after the training

intervention, the book group had not improved their performance ($M = 0.370$, $SD = 0.103$). The block group, however, had become significantly better ($M = 0.438$, $SD = 0.172$).

3.3 | Effect of intervention on ANS acuity

The descriptive statistics for infants' preference scores on the numerical change detection task can be seen in Table 2. We predicted that the block-training group should outperform the book group on the numerosity discrimination task at post-test. In order to test this prediction, we submitted the preference score from the numerosity discrimination task to a GLMM. The resulting model showed a significant main effect of ratio ($\chi^2(2) = 11.87$, $p < .01$), but no main effect of condition ($\chi^2(1) = 0.923$, $p = .337$) or time point ($\chi^2(1) = 0.095$, $p = .344$) and no significant interactions (all $ps > .11$).

This indicates that infants, in both groups and at both time points, had higher preference scores on the easier ratio compared to the harder ratio ($M_{1:4} = 0.567$, $SD = 0.157$; $M_{1:2} = 0.524$, $SD = 0.130$; $M_{2:3} = 0.489$, $SD = 0.156$), which is a pattern that is expected and often found when measuring ANS performance. In contrast to our prediction, the block group did not outperform the book group on numerosity discrimination after the training intervention. It also seems that infants, regardless of training group, did not improve their numerosity discrimination over time.

3.4 | Attention

It is possible that the observed visual form perception training effect could be explained by an increase in domain general attention, and not an improvement in visual form sensitivity. To test this possibility, we analysed the infants' scores on the visual attention task using a GLMM. The model showed that there was no significant interaction between condition and time point ($\chi^2(1) = 0.073$, $p = .787$) and no main effect of condition ($\chi^2(1) = 0.034$, $p = .854$) or time point ($\chi^2(1) = 0.003$, $p = .953$). This shows that infants in the block group did not improve their attention compared to the book group. In fact, neither training group had higher attention scores at post-test compared to pretest. It is therefore unlikely that the training effect on visual form perception can be explained by an increase in domain general attention.

3.5 | Effect of intervention on object exploration

We also predicted that the block group should show higher levels of object exploration compared to the book group after the intervention. We entered the object exploration score into a GLMM and the resulting model showed that there was no significant interaction between condition and time point ($\chi^2(1) = 0.794$, $p = .373$) and no significant main effect of time point ($\chi^2(1) = 1.832$, $p = .176$) or condition

TABLE 1 Visual form perception task, mean proportion score and standard deviation in parentheses

	Pretest		Post-test	
	60°	90°	60°	90°
Blocks	0.36 (0.21)	0.31 (0.13)	0.49 (0.17)	0.39 (0.18)
Book	0.42 (0.16)	0.36 (0.15)	0.41 (0.16)	0.32 (0.16)

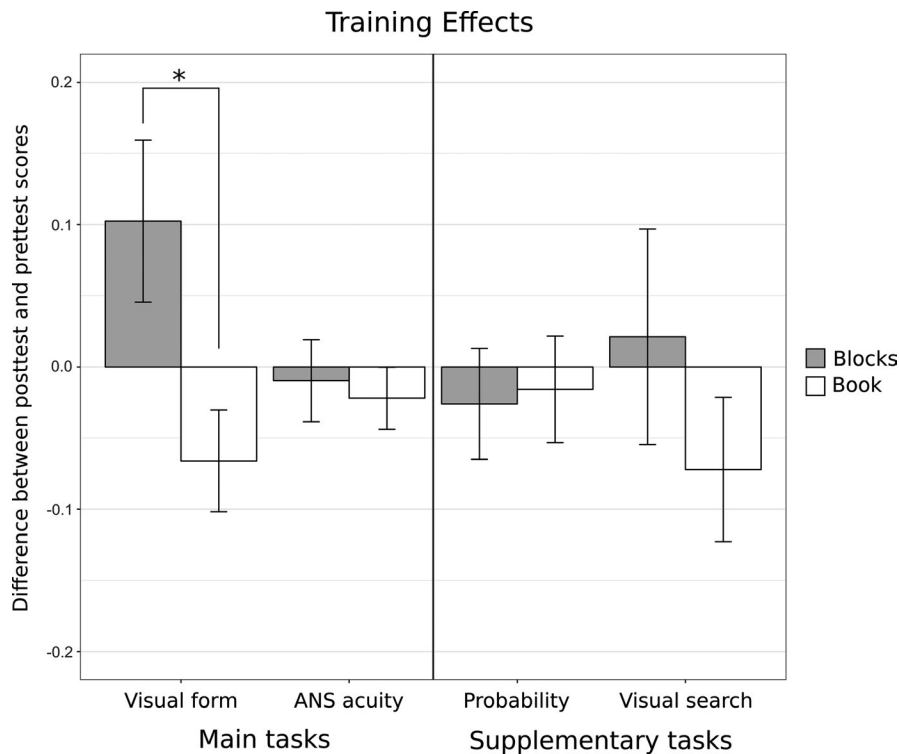


FIGURE 2 Mean difference between post-test and pretest scores for main (visual form perception and approximate number system acuity) and supplementary (probability perception and visual search) eye-tracking tasks for block group (grey) and book group (white). Error bars denote standard error of the mean. The asterisk indicates that the comparison is significant at $p < .05$ level

Ratio	Pretest			Post-test		
	1:4	1:2	2:3	1:4	1:2	2:3
Blocks	0.55 (0.20)	0.47 (0.18)	0.51 (0.20)	0.58 (0.16)	0.49 (0.15)	0.43 (0.23)
Book	0.61 (0.13)	0.55 (0.15)	0.52 (0.18)	0.52 (0.20)	0.60 (0.20)	0.48 (0.20)

TABLE 2 Approximate number system acuity task, mean proportion score and standard deviation in parentheses

($\chi^2(1) = 0.448, p = .503$). In other words, the block training did not affect the amount of object exploration on this task.

3.6 | Supplementary tasks: probability perception, visual search and approximate addition

To further test the specificity of the training effect on visual form perception, we analysed infants' performance on two, unrelated to the active exploration hypothesis, eye-tracking tasks – probability perception and visual search. Please see Table S1 for descriptive statistics. The analyses showed that the block training did not affect infants' probability perception nor did it affect their performance on the visual search task (see Supporting Information for full details). This indicates that the training effect seen on visual form perception was not merely a general improvement on preferential looking tasks on the eye tracker and further it suggests that the intervention specifically increased infants' ability to process the shape of objects and not their visual perception in general. Finally, we also explored if the intervention would improve infants' ability to estimate the outcome of a $5 + 5$ addition event. Results indicated that this was not the case; block training did not seem to affect infants' ability to perform approximate addition.

4 | DISCUSSION

Infants have the ability to intuitively process visual forms and numerosities and there are individual differences in these two abilities already in infancy. We hypothesized that the individual differences may stem from early motor experiences, specifically differences in motor-dependent exploration. In the current study, we set out to test the two parts of this hypothesized process. We investigated if a minimal intervention increased visual form perception in 8- to 10-month old infants and secondly, if increased visual form perception would lead to improvements in ANS acuity. Infants, who were assigned to actively play with blocks together with their caregivers, demonstrated better visual form sensitivity after the intervention compared to a control group who read books instead of played. Follow-up analyses of an attention task, an unrelated preferential looking task and a visual search task showed that the improvement in visual form perception could not be explained by domain general improvements in attention or visual perception. We could not, however, observe an effect of the active exploration intervention on ANS acuity. We will now look at each step of our hypothesis individually, starting with the proposed connection between motor ability, active exploration and visual form perception.



While previous research has provided tentative evidence for a link between motor development and spatial abilities in general (Frick & Möhring, 2013, 2016; Möhring & Frick, 2013; Slone et al., 2018), our results are the first to provide direct evidence that motor experiences in infancy impacts visual form perception. A minimal intervention consisting of block play once a day, for 8 weeks, caused infants to become better at detecting a deviant visual form among distractors. This finding provides support for the first part of our active exploration hypothesis. In line with the hypothesis, we expect that the intervention affected visual form sensitivity through infants being given more opportunities to practice reaching for and manipulating objects. These motor experiences in turn caused infants to pay more attention to properties that are important for interacting with objects. This, over time, strengthened infants' ability to process object properties, here operationalized as visual form perception. A caveat to this conclusion is the possibility that visual form perception improved during our 8-week study period due to maturation, and that the book reading intervention suppressed such a maturation effect, possibly through parents in the book condition having engaged less in activities similar to block play outside of the training sessions. However, we find this an unlikely interpretation as parents were instructed not to change their behaviour outside of the training sessions and because the level of parent engagement was similar in both conditions.

Our finding goes beyond previous research in two ways. While it has previously been shown that motor experiences with objects affects visual processing of those same objects immediately after the experience (Möhring & Frick, 2013; Slone et al., 2018), our finding goes further by showing that motor experiences can affect object processing in a completely unrelated task, with very different stimuli, even after there has been a delay between the motor experiences and testing. Furthermore, we are able to show that the intervention specifically improved infants' ability to process the shape of visual forms instead of just improving their visual perception in general, since there was no effect of the intervention on the visual search task.

In the second step of our hypothesis, we proposed that improved visual form perception causes infants to process richer magnitude input, which, over time, increases the acuity of the ANS. In contrast to our prediction, our data indicated no improvement in ANS acuity from pre- to post-test, in either group. There are at least two potential reasons why we did not see any improvements in ANS acuity. First, perhaps enhanced visual form perception and magnitude processing does not affect the ANS. If so, this would be in line with the core knowledge perspective (Carey, 2009) which views the ANS as an encapsulated, numerosity dedicated system that should not be affected by improvements in other perceptual domains. However, another possibility is that it takes time for an improvement in visual form perception to transfer to an improvement in ANS acuity. According to our hypothesis, improved visual form perception provides richer input to the ANS but it is possible that the ANS needs time to accumulate this richer input before improvements in acuity are observed. If this is the case, then we would only expect improvements in ANS acuity after the ANS has had enough time to

accumulate the improved input. Our intervention lasted for 8 full weeks and we do not know when the intervention visual form improvements emerged. It is therefore difficult to know how long the active exploration group had benefitted from improved visual form perception. Because a potential training effect would likely be quite small and because of problems with attrition in longitudinal studies, we did not believe that our sample size was large enough to warrant following the infants over a longer time period. However, it is possible that ANS acuity improvements will emerge in the active exploration group over time. In light of this possibility, it will be important to design future studies investigating the same question with a post-test immediately after the intervention and a follow-up test at a later time point, in order to detect possible delayed effects on ANS acuity.

Despite not finding a training effect on ANS acuity, our study contributes to the field of infant numerical cognition by introducing and testing an updated method of assessing ANS acuity in infants. Our adapted version of Libertus and Brannon's (2010) numerical change detection paradigm can be run on an eye tracker that allows for more automatic and detailed analyses of looking behaviour. Also, the shorter trials give the possibility of testing infants on multiple trials and ratios, which could give more accurate assessments of an individual infant's ANS acuity. Our data show that we were able to replicate the signature numerosity discrimination results, with higher proportion scores on easier ratios. However, our results deviate slightly from previous findings (Libertus & Brannon, 2010; Starr, Libertus, & Brannon, 2013) in that we find lower performance on the more difficult ratios. We believe that this can be explained by our paradigm being more difficult, partly due to the shorter trials (10 s vs. 60 s), which give infants less time to form a preference for the changing stream. Our paradigm is also more complex in that both image streams are presented on the same screen which may lead infants to scan the stimuli differently. The fact that we did not see a general improvement in ANS acuity across both groups from 8 to 10 months is perhaps surprising given that ANS acuity improves with age (Feigenson et al., 2004). However, to our knowledge no study has actually measured ANS development between 8 and 10 months of age and it is therefore possible that general maturation of the ANS cannot be seen in such a short time period.

Furthermore, in contrast to what we predicted, the active exploration group did not spend more time exploring a complex toy after the intervention compared to the book group. Perhaps the improvement in visual form perception was due to the training providing opportunities to play and explore rather than changing infants' general object-directed attention or motor behaviour. Or it could be that the intervention impacted the quality of infants' exploration or the strategy of their exploration. If so, this would not easily be captured by our coding scheme. The chosen assessment may also have been problematic for our chosen age group given that it was developed for toddlers (Libertus et al., 2016). In our sample, many infants became frustrated with having to remain seated during the assessment and several infants could therefore not complete the assessment. In the original study, this was not a problem because the toddlers could chose to stand or sit while exploring.

In sum, the results of the current intervention study provide support for the first step of the active exploration hypothesis – increasing opportunities for motor-dependent exploration improves infants' sensitivity to the shape of visual forms. But we cannot yet confirm, or reject, the hypothesis' second step – that improved visual form perception impacts ANS acuity. Our study is an important first step in investigating the origins of individual differences in visual form perception and ANS acuity but more research is needed to fully evaluate our hypothesized process.

In addition to providing evidence for the first part of the active exploration hypothesis, the current study contributes with several other insights. First, our results add to a growing body of research demonstrating the importance of early motor experiences for cognitive development (Bakker et al., 2015; Gottwald et al., 2016; Ridler et al., 2006; Sommerville, Woodward, & Needham, 2005). Secondly, we contribute causal evidence to the literature showing a correlation between motor skill and spatial abilities (Frick & Möhring, 2013, 2016; Soska et al., 2010). Lastly, we broaden the infant motor training literature by providing a novel intervention that can successfully be used with older infants. Previous training studies have relied on sticky mittens interventions, which are limited in that they are only appropriate for pre-reaching infants (around 2–4 months of age). Our active exploration intervention, on the other hand, has the potential to be used with infants from when they are able to sit (around 6 months) and up.

Certainly, there are limitations to the current study. For example, we cannot precisely pinpoint what part of the active exploration intervention caused the improvement in visual form sensitivity. Given that the training sessions contained many aspects, such as reaching, banging, touching and mouthing, we cannot know if it was the combination of these aspects or one behaviour in particular that was effective. Future studies including tasks which tap into other aspects of spatial abilities, for example mental rotation (e.g. Lauer & Lourenco, 2016), might help disentangle these possibilities. It is also not possible to completely rule out that the current minimal intervention caused caregivers to change something in their interactions with the infants outside the training session or that our results were diluted by the fact that parents already play with blocks and read books to their infants at this age. We attempted to control for this by instructing caregivers to only use the blocks 5 min a day. However, the block playing may have encouraged caregivers to participate in even more active interactions with their infant in a range of settings. In fact, a previous study suggests that sticky mittens training administered by an experimenter rather than a caregiver is not effective (Williams et al., 2015). It would be an interesting venue for future studies to investigate if stronger effects of the training can be found also in our paradigm if caregivers are allowed to use the study materials outside of the training sessions. Also, there may have been differences between caregivers in how well they were able to implement the intervention. This may have added noise to our results but given that we did find a positive effect of the intervention, it was most likely not a large problem. Finally, our results indicated that infants' proportion score in the visual form task was somewhat higher

in the 60° than in the 90° condition, although above chance in both conditions (c.f. Lindskog et al., 2019). Because we conceptualized the 90° condition as being the easier condition, this is somewhat surprising. One possible reason for our results is that infants were quicker to find the target form in the 90° than in the 60° trials. If so we would expect them to start looking at the deviant forms after having found the target form, which in turn would result in a lower proportion score. Indeed, in a previous study using the same task (Lindskog et al., 2019), there was a trend in the data suggesting that infants detect the target form quicker in the 90° than in the 60° condition.

In a broader perspective, our findings highlight that the type of activities caregivers choose to engage in with their infant impact infants' cognitive development. While reading to an infant, which caregivers are often encouraged to do, has positive effects on sustained attention and language development (Vally et al., 2015), our results instead stress the importance of play and exploration. If infants are given more opportunities to explore and play with different objects and materials they will become better at processing visual forms which should, over time, be valuable for their understanding of geometrical concepts. Possibly, such understanding might also set families on a trajectory that includes even more activities of play and exploration in the years going forward, which might have the potential to set the stage for future success in STEM-related disciplines.

ACKNOWLEDGEMENTS

The project was funded by a grant from Riksbankens Jubileumsfond to ML (P15-0430:1). We thank members of Uppsala Child and Baby Lab for comments on the manuscript, Tina Altdörfer and Mattias Englin for assisting the data collection, and all participating families.

CONFLICT OF INTEREST

The authors declare that we have no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Schröder E, Gredebäck G, Gunnarsson J, Lindskog M. Play enhances visual form perception in infancy—an active training study. *Dev Sci*. 2020;23:e12923. <https://doi.org/10.1111/desc.12923>