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Development of exploration of spatial-relational object properties in the second and third years of life

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ABSTRACT

Within a perception–action framework, exploration is seen as a driving force in young children's development. Through exploration, children become skilled in perceiving the affordances in their environment and acting on them. Using a perception–action framework, the current study examined the development of children's exploration of the spatial-relational properties of objects such as the possibility of containing or stacking. A total of 61 children, belonging to two age cohorts, were followed from 9 to 24 months and from 20 to 36 months of age, respectively. Exploration of a standard set of objects was observed in five home visits in each cohort conducted every 4 months. A cohort-sequential augmented growth model for categorical data, incorporating assumptions of item response theory, was constructed that fitted the data well, showing that the development of exploration of spatial-relational object properties follows an overlapping waves pattern. This is in line with Siegler's model (*Emerging Minds*, 1996), which suggested that skill development can be seen as ebbing and flowing of alternative (simple and advanced) behaviors. Although the probability of observing the more complex forms of exploration increased with age, the simpler forms did not disappear altogether but only became less probable. Findings support a perception–action view on development. Individual

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differences in observed exploration and their relations with other variables, as well as future directions for research, are discussed.

Introduction

According to perception–action theory, such as elaborated by Eleanor Gibson, children play an active role in their own development. They perceive information that elicits actions, and these actions in turn provide new information to be perceived, specifying new actions. Children's growing knowledge of the world and their increasing ability to act adaptively and skillfully in it are grounded in these continuously recurring perception–action loops, referred to as exploration (Adolph, Eppler, Marin, Weise, & Wechsler Clearfield, 2000; J. J. Gibson, 1979; E. J. Gibson, 1988; E. J. Gibson & Pick, 2000).

Exploration is in many ways the key to development. Extensive empirical work shows that young children's exploration behavior is related to advances in several domains of development (e.g., Needham, 2000; Needham, Barrett, & Peterman, 2002; Soska, Adolph, & Johnson, 2010). Exploration of the spatial properties of objects and of the spatial relations between objects (henceforth spatial-relational object properties) is a special kind of exploration, referring to the perceiving of and acting on properties of objects such as the possibility of containing, stacking, fitting into each other, and pulling out. Correlational evidence suggests that the exploration of objects and spaces is strongly related to the development of spatial cognition (Campos, Anderson, & Telzrow, 2009; Campos et al., 2000; Clearfield, 2004; Oudgenoeg-Paz, Leseman, & Volman, 2014, 2015). Spatial cognition in turn has been shown to be highly relevant for success in various academic disciplines such as science, mathematics, and language as well as for complex social behaviors involving perspective taking (Creem-Regehr, Gagnon, Geuss, & Stefanucci, 2013; Gathercole, Alloway, Willis, & Adams, 2006; for a review, see Newcombe, Uttal, & Sauter, 2013).

Research on the development of object exploration has predominantly focused on the exploration of single objects during the first year of life (e.g., Eppler, 1995; Galloway & Thelen, 2004; Soska et al., 2010). Less is known about the development of object exploration after the first year of life. Moreover, research into children's object exploration has rarely focused on exploration of the spatial-relational properties of objects or on the possibilities of combining objects entailed by these properties. The current study adds to the evidence by examining the development of children's exploration of the spatial-relational properties of objects from the end of the first year into the third year of life.

Studies investigating single object exploration in infants have mainly focused on actions such as fingering, mouthing, and shaking that enable infants to acquire different kinds of information about the objects through different sensory modalities (e.g., Eppler, 1995; Lobo & Galloway, 2008; Ruff, 1984). Exploration of multiple objects simultaneously (e.g., holding two objects at the same time) has been reported to appear in infants as young as 7 or 8 months, but multiple object exploration seems to become an established part of the behavioral repertoire of typically developing children only from the age of 11 months onward (Kotwica, Ferre, & Michel, 2008). During the second year of life, once two or more objects can be manipulated together, exploration becomes gradually more complex as infants start to explore the spatial relations between objects and become increasingly skilled in making combinations of increasing complexity (e.g., inserting an object into another object, pulling an object out of another object, stacking objects). Exploration of spatial-relational properties is displayed to a greater extent when infants are presented with objects with complementary spatial properties that afford such combinations, suggesting that the information structures in the environment play a critical role in the development of exploration (for a review, see Greaves, Imms, Krumlinde, Dodd, & Eliasson, 2012; see also Fagard & Jacquet, 1989; Kimmerle, Ferre, Kotwica, & Michel, 2010; Ramsay, 1985).

In line with Lockman (2000), who applied a perception–action perspective to tool-use development, we argue here that the development of exploration from exploring single objects to exploring multiple objects without combining them, and to combining objects, requires detecting the spatial-relational affordances of single objects as well as detecting what Lockman called *affordance relations* between objects and which we refer to here as *relational affordances*. For example, discovering the affordance of insertion requires perception of the elementary affordances of the separate objects first (e.g., having an opening and size relations enabling containment). Through perception–action routines, infants discover the actions that separate objects afford. By performing the actions specified by elementary affordances repeatedly, also with similar objects in different situations, infants become increasingly skilled in acting on these affordances. This process sets the stage for discovering new, more complex affordances that in turn specify more complex actions such as spatially combining objects (E. J. Gibson, 1988; E. J. Gibson & Pick, 2000). We use a slightly different term than the term used by Lockman in order to stress the novel and complex nature of these affordances, being more than just a combination of the affordances of separate objects.

The affordances to be discovered are specified as a result of both the child's changing and variable skills to exploit affordances and the information structures in the environment. Therefore, development of object exploration in this view is driven both by recurrent perception–action cycles, leading to increasing skill and to the discovery of increasingly complex affordances, *and* by the information structures in the environment (J. J. Gibson, 1979; E. J. Gibson, 1988). In addition to these driving forces, the development of object exploration is obviously constrained by the neuromuscular development of hand skills (e.g., ability for grasping, in-hand manipulation, and bimanual manipulation of objects; Greaves et al., 2012) and (changes in) body-scaled relations for grasping (e.g., does the size of an object afford the child to grasp it with one hand, or is grasping with two hands needed?; van der Kamp, Savelsbergh, & Davis, 1998). These constraints are important to bear in mind, but they were not the main focus of the current study.

Support for the perception–action view on development of object exploration comes from a cross-sectional study by Bourgeois, Khawar, Neal, and Lockman (2005) into the development of object–surface combinations. The findings of that study suggest that complex actions in which children establish relations between objects and surfaces emerge from previous exploration of the properties of these objects and surfaces separately. Separate exploration of the properties of objects and surfaces sets the stage for detecting affordances that specify a relation between object and surface, leading to action (i.e., exploiting the relational affordances by making the object–surface combination). For instance, 6-month-old infants explored object properties (e.g., softness and hardness of objects by squeezing and scratching) and surface properties (e.g., liquidity, discontinuity, flexibility, and rigidness by slapping, pressing, rubbing, and picking), but they hardly related objects to surfaces. Interestingly, 10-month-old infants also explored object and surface properties separately when presented with a new set of objects. However, the 10-month-olds also related objects to surfaces much more frequently (e.g., pressing objects into different surfaces, rubbing objects on surfaces, banging objects on surfaces), with the particular action shown depending on the specific properties of both the objects and the surfaces. The youngest infants always started with either separate object or surface exploration and only occasionally ended with object–surface relational exploration. The oldest infants mostly still started with separate object or surface exploration but soon changed to exploration of the relations between the two within the session (Bourgeois et al., 2005). Note that the affordances explored in Bourgeois and colleagues' study are spatial-relational in the sense that they involve relations such as *on, in, against,* and *through*. Takeshita et al. (2005) investigated the development of spatial-relational object exploration in infant chimpanzees longitudinally and reported similar results; the infant chimpanzees followed a developmental trajectory from the exploration of the spatial-relational properties of single objects and surfaces to the exploration of combinations of objects and surfaces (i.e., detecting and exploiting the relational affordances). These results closely match the results of Bourgeois and colleagues (2005). However, longitudinal evidence pertaining to the development of spatial-relational object exploration in human infants, taking a perception–action perspective, is still lacking.

The development of spatial-relational object exploration, and in particular the use of combinations, has also been studied within a play development perspective, where play development is considered as a succession of stages of increasing cognitive complexity. Object exploration (including, among others, the making of combinations) in this research is seen as an early stage to pass in play development, with symbolic play as the cognitively most complex level toward which development is heading (e.g., Belsky & Most, 1981; Schneider, 2009; van Schijndel, Singer, van der Maas, & Raijmakers, 2010).

Considered from a perception–action approach, exploration cannot be seen as merely a developmental stage. Even while children engage in symbolic play (e.g., pretending to cook soup), they are still using their basic skill to perceive and act on the spatial-relational object properties (e.g., size of the spoon in relation to the pan, space in the pan for the spoon and pretend soup). Thus, spatial-relational object exploration is a separate skill that supports functional and symbolic play but does not coincide with these play skills.

A typical and widely discussed problem of stage theories is how to explain intra-individual variability, that is, the frequently observed temporary regressions to a previous, less advanced stage and temporary progressions to a future, more advanced stage (Fischer & Bidell, 2006; Siegler, 1996; van Dijk & van Geert, 2007; van Geert & van Dijk, 2002). The perception–action account may provide an alternative perspective on this issue. In this view, (seemingly) higher order behaviors or concepts are thought to be situated and to emerge or to be "softly assembled" in real time from the series of (simple) perception–action loops that constitute every specific activity. For instance, temporary regressions can occur when well-learned affordances pertaining to extensively explored objects (children showing skill in their actions with these objects) are to be discovered again because new objects are encountered with slightly different physical properties or because well-explored objects are encountered in a new constellation with other objects. In these cases, the context of the task and children's previous experience do not (immediately) support the emergence or soft assembly of more advanced forms of behavior, and so simpler forms are used. Developmental progress can occur if extensively explored objects are encountered in a constellation in which children can perceive more complex relational affordances that specify more complex actions. In this view, simple perception–action routines do not disappear during the course of development but rather continue to provide the basis on which new, more complex perception–action routines can emerge (Fischer & Bidell, 2006; Lockman, 2000; Siegler, 1996; Thelen & Smith, 1994). Therefore, the emergence of complex and developmentally more advanced behaviors (e.g., making object–object combinations) is expected to go together with increased variability of skill at the point of emergence, showing both temporary regressions and progressions. The higher level skill is expected to become more stable the more the complex affordance structure is explored (Lockman, 2000; Siegler, 1996; Thelen & Smith, 1994; van Geert & van Dijk, 2002).

Following this line of reasoning, Siegler (1996) suggested, as an alternative to stage theories, that the development of particular skills can be described as the ebbing and flowing of alternative behaviors, with changes over time in the likelihood that certain behaviors will be observed. Developmental progress is marked by a decrease in the observed frequency of less mature behaviors and an increase in the observed frequency of more mature behaviors, resulting in the typical pattern of overlapping waves. Until recently, Siegler's model was used only as a metaphor but not statistically tested. Using recent advances in latent growth modeling and item response theory (Boom, 2015), van der Ven, Boom, Kroesbergen, and Leseman (2012) successfully modeled the development of mathematical problem-solving strategies in 8-year-olds' multiplication learning as overlapping waves, fully in line with Siegler's (1996) theoretical proposal. The current study applied this approach to the development of young children's exploration of spatial-relational object properties. It is important to note that Siegler's model refers to the choice between alternative strategies, which are thought to be internally represented in the child's mind. In our approach, we do not need the assumption of mental representation because we focus on the choice between alternative behaviors that are assumed to be determined by the child's level of skill and the affordances specified by the constellation of objects. The exploration behaviors we observe are thought to emerge in real time as a result of the interaction among task constraints, previous experience of the child with these or similar tasks, the child's posture, motivation, and so on.

The current study examined the development of young children's exploration of spatial-relational object properties over a period from 9 to 36 months of age. To cover this extended age range, an augmented cohort sequential approach involving two age cohorts was used (Duncan, Duncan, & Strycker, 2006). The study focused specifically on children's exploration of the properties of objects that afford spatial combinations. Exploration behaviors of different levels of complexity observed at different time points were modeled as overlapping waves, with the shapes of the waves and their timing being a function of the complexity of the affordances explored and children's growing skill to pick up and exploit these affordances. A clear advantage of this approach is that it allows examining both the development of group means, as in Bourgeois and colleagues' (2005) study, *and* children's individual developmental trajectories, including intra-individual variability (see van Geert & van Dijk, 2002, for a discussion on the importance of studying intra-individual variability). Moreover, using this approach, developmental trajectories can be related to background variables that have been shown to predict exploration and spatial cognition, in particular gender and socioeconomic status (Hart, Petrill, Deater Deckard, & Thompson, 2007; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005), and to concurrent measures of spatial cognition to evaluate the validity of the current approach.

In the current study, children were observed while exploring a standard set of objects that was carefully selected to enable a variety of spatial-relational affordances of different complexity (for a review on the importance of object selection, see Greaves et al., 2012). In contrast to most previous studies of exploration behavior (e.g., Bourgeois et al., 2005; Eppler, 1995; Soska et al., 2010), observations in the current study were conducted at children's homes rather than in a lab setting. Children were allowed to play on the floor of the living room or the play room at home and to move around while exploring. This setting was chosen in order to elicit behavior that optimally resembles children's natural exploration behavior, thereby increasing the ecological validity of the study.

Method

Design and participants

The participants belonged to two cohorts. Both cohorts took part in five measurement waves between 9 and 24 months of age for the younger cohort ($n = 30$, 53% girls) and between 20 and 36 months of age for the older cohort ($n = 32$, 56% girls). Measurements were conducted at intervals of 4 months, with the exception of the first interval in the younger cohort, which lasted 3 months. The two cohorts had overlapping measurement moments at 20 and 24 months of age. The participants were recruited through day-care centers in the municipality of Utrecht, The Netherlands, and through an address list made available by the municipality of Utrecht. Only children from Dutch-speaking families without known medical or developmental disorders were included in the study. Informed consent was obtained for all children.

Two children in the younger cohort and one child in the older cohort took part in only the first two measurements. In addition, some of the observation data were missing due to technical problems or to children's unwillingness to cooperate. This resulted in 5.3% of the observation data missing. Five children missed data from one measurement moment, and one child missed data from two measurement moments. Details about the total number and mean age of the children at each measurement moment can be found in Table 1. Finally, two children refused to do the spatial memory task during the third measurement moment, and data on socioeconomic status (SES) were missing for four children due to incomplete questionnaires. Data of these children were included in the analyses of development of exploration but excluded from analyses involving spatial memory and SES (see "Analysis" section below for more detail).

Table 1
Sample size, mean children's age, and standard deviations divided by cohort for all measurement moments.

Measurement	Younger cohort		Older cohort		Total	
	n	M_{age}[a] (*SD*)	*n*	M_{age}[a] (*SD*)	*N*	M_{age}[a] (*SD*)
9 months	30	9.21 (0.47)	–	–	30	9.21 (0.47)
12 months	29	12.16 (0.47)	–	–	29	12.16 (0.47)
16 months	27	16.05 (0.37)	–	–	27	16.05 (0.37)
20 months	27	20.26 (0.29)	31	20.75 (0.61)	58	20.52 (0.54)
24 months	28	24.12 (0.33)	30	24.14 (0.30)	58	24.13 (0.31)
28 months	–	–	29	27.92 (0.38)	29	27.92 (0.38)
32 months	–	–	31	32.14 (0.33)	31	32.14 (0.33)
36 months	–	–	29	36.05 (0.25)	29	36.05 (0.25)

[a] Age in months.

Procedure

Exploration was observed during home visits. Children were filmed while exploring a standard set of objects brought along by the researcher for 8 min. The objects included a transparent container with foam blocks in different sizes and shapes that can be fitted into each other, plastic building blocks, and nesting cups. See Fig. 1 for a photo of the objects used. The objects were laid out on the floor in a standard manner. Children's posture was not limited in any way. At 9 months of age, infants were mostly lying down on their bellies or sitting. At the other ages, children were mostly sitting down or (occasionally) crawling or walking. The films were edited to remove interruptions (e.g., stopping for changing diapers or drinking). Exploration behavior was scored based on the first 4 min of uninterrupted play. Spatial memory was also measured during the home visits using a test administered by trained research assistants. Background information such as gender and SES was obtained through parental questionnaires. The families were rewarded with a small gift for the child at each measurement moment.

Measures

Exploration of spatial-relational object properties

Exploration of spatial-relational object properties was scored based on 4-min video-recordings. Each 4-min recording was divided into 24 intervals of 10 s each. Per interval, the activities of the child and duration of each activity were noted. Next, a score was given to each interval based on the most dominant (longest enduring) activity. *No exploration* was scored when the child was not engaged with any of the objects (also not looking at any of the objects). *Exploration involving a single object* was scored when the child was manipulating and/or looking at a single object (i.e., looking without manipulation and manipulating without looking were also considered as exploration). A few examples of this kind of exploration include picking up, rotating, mouthing, and hitting (all of these performed with a single object). *Exploration involving multiple objects* was scored when the child was manipulating or looking at two or more objects (e.g., when objects were lying next to each other) but was not trying to combine the objects. Examples of this kind of exploration include holding one object while manipulating another object, holding or mouthing one object and looking at another object, looking at two or more objects simultaneously, picking up multiple objects, throwing or putting down a few objects at once (without ordering them according to shape or size), and mouthing two objects simultaneously. *Exploration involving combinations of objects* was scored when the child was bringing two or more objects in relation to one another. Examples of this kind of exploration include inserting an object into another object, stacking, fitting an object into another object, removing objects out of other objects containing them, and ordering objects according to shape (e.g., letting the flat ends touch) or according to size rather than randomly putting objects near each other. If two or more activities lasted equally long during an interval, the score representing the (theoretically) more complex activity was

Fig. 1. Objects used in the observations.

assigned to that interval. Thus, for each 4-min video observation, each of the 24 intervals received a score of either 1 (no exploration), 2 (exploring a single object), 3 (exploring multiple objects), or 4 (exploration using combinations). Trained coders scored the video fragments. Two coders independently scored 20.5% of the fragments. Cohen's kappa ranged between .67 and .76, with a mean value of .71 (*SD* = .02) (all kappa values but one were >.70).

Spatial memory

Spatial memory was assessed using an adaptation of the memory for location task developed by Caravale, Tozzi, Albino, and Vicari (2005). Children were presented with a row of identical cups and viewed a toy being hidden under one of the cups. After a short delay, while being distracted by the experimenter, children were asked to search for the toy. To make the task more difficult, the number of toys (1 or 2), number of cups (4 or 6), and length of the delay (1–11 s) were manipulated. The level of difficulty of the items was determined in pilot testing, and the results can be found in Table 2. Testing started with a fixed starting item that varied per age group (see Table 2). If children failed the starting item, they were given a second identical item. If they were successful on the starting item in either the first *or* second attempt, they were given a next item of one difficulty level up. If they passed this item (again on the first *or* second attempt), they were again given an item of one difficulty level up until they either failed an item twice or completed the item with the highest level of difficulty. If children failed both attempts of the starting item, they were given a next item of one difficulty level down until they were successful (again on the first *or* second attempt) or until the lowest difficulty level was reached. The final score was the highest level of difficulty completed with success. To shorten testing time, items involving two toys were not administered at 16 months of age because pilot testing indicated that this was too difficult for this age. The score ranges, therefore, were 0 to 9 at 28 months and 0 to 6 at 16 months of age.

Socioeconomic status

SES was based on the highest completed education level of both parents scored on a 7-point scale ranging from 1 (elementary school) to 7 (university degree) and the status of their current occupation on the Dutch national job index list, ranking jobs according to required education level, ranging from 1 (elementary vocation level) to 5 (academic vocation level) (Centraal Bureau voor de Statistiek, 2001). SES was computed as the mean of both parents' education and occupation levels after *Z*-transformation (Cronbach's $\alpha = .73$).

Analysis

The first step of the analysis involved a close examination of the patterns in the raw data. For each measurement occasion, the frequencies of the four different forms of exploration that were observed in the 24 intervals per 4-min observation were calculated. One of the assumptions underlying the

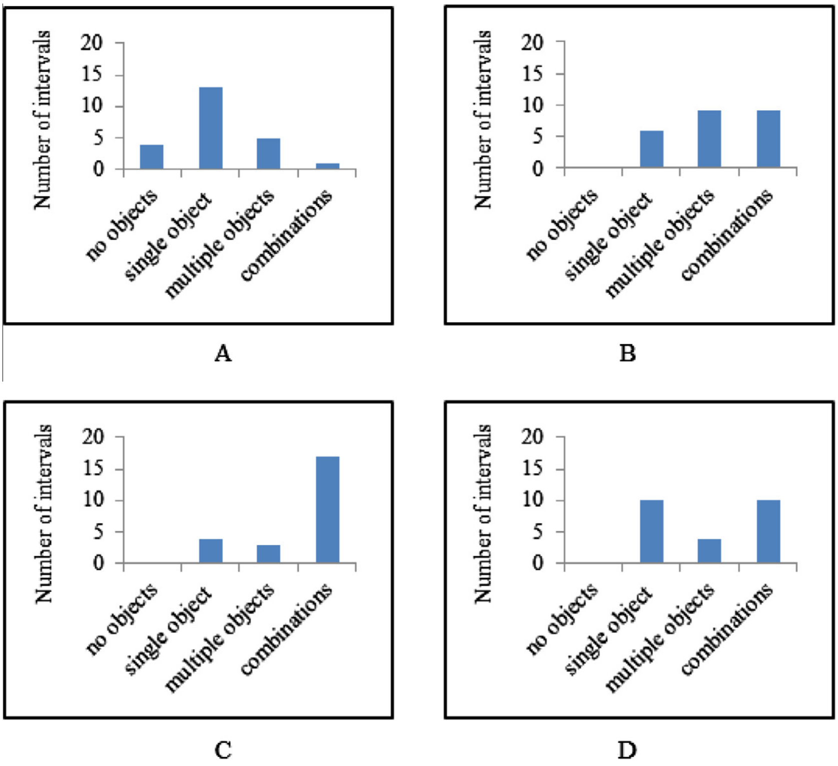
Table 2
Items in order of difficulty in memory for location task.

Difficulty level	Number of cups/Number of toys hidden/delay in seconds
1	4/1/1
2	4/1/4
3[a]	6/1/1
4	6/1/5
5	4/1/9
6	6/1/11
7[b]	6/2/1
8	6/2/5
9	6/2/11

[a] Starting item at 16 months of age.
[b] Starting item at 28 months of age.

model, based on item response theory (IRT), is that the distinguished forms of exploration constitute an ordinal scale. Therefore, we expected to find clear peaks signaling the form of exploration the child uses most frequently at a particular point in time. Fig. 2 presents examples from the raw data. Fig. 2A, B and C show clear peaks in accordance with the IRT assumption. To correct for measurement error caused by the fact that some actions carried over from one 10-s interval to the next, whereas others ended or started in the middle of an interval, only differences in frequencies larger than 10% of the intervals were considered meaningful; in case of smaller differences, the frequency counts were treated as being equal. Note that it is possible to find two adjacent exploration forms as equally frequent without violating the IRT assumption (see Fig. 2B). However, finding two *non*-adjacent forms as both most frequent is inconsistent with the IRT assumption (see Fig. 2D). Two observations (out of a total of >250) showed this pattern (one child at 12 months and one child at 20 months of age). Closer examination of these observations revealed that although both had more than 12 valid fragments, the children were distracted to some degree during their exploration due to external factors (e.g., a ringing phone). Therefore, these observations were considered as erroneous and treated as missing data.

Fig. 3 shows the frequency of each form of exploration per age group, revealing that at the younger ages children showed single object or multiple object exploration most frequently. With increasing age, however, combinations gradually became the most frequent form of exploration. *No exploration* was never the most frequent form of behavior in the current sample. Therefore, this level was not informative for the purpose of the study and not included in further analyses in order to keep the model as parsimonious as possible. Furthermore, at the oldest age, a ceiling effect was manifest; nearly all children showed mainly combinations during exploration, indicating the emergence of a stable pattern. Combining objects appears to be a well-established skill at this age for nearly all



A

B

C

D

Fig. 2. Raw data of individual children demonstrating the patterns of frequency of forms of exploration within 4 min of observation.

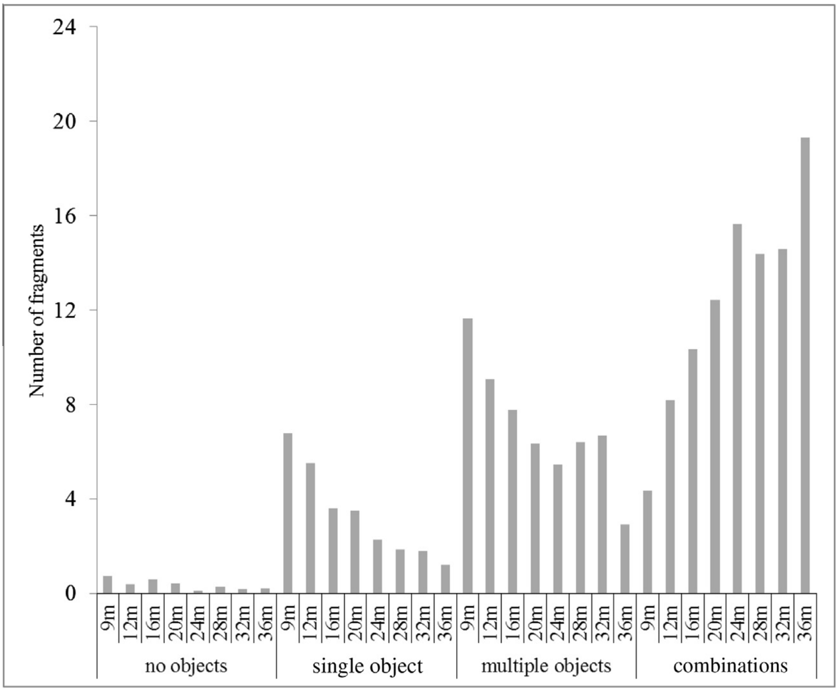


Fig. 3. Mean number of intervals scored per exploration form per age group. m, months.

children in the current sample. Due to the ceiling effect and the resulting severely limited variance in scores, the data from the last measurement moment at 36 months of age could not be used in further analyses. In summary, close examination of the data confirmed that coding in terms of the most frequent form of exploration would be appropriate for this data set. Exploration was coded as a categorical value ranging from exploration with single objects (coded as 2) to the making of combinations (coded as 4), for each child, at each measurement occasion. When two adjacent forms were both the most frequent forms and roughly equally frequent (within 10% difference), the lower score was awarded to avoid overestimation of children's level of exploration.

To model the longitudinal change in the frequencies of the different exploration forms, a latent growth model (LGM) for categorical data was used. LGM can be used to estimate the mean level (across ages) of a developing ability in a particular sample (intercept), the mean growth of this ability over time (slope), and the inter-individual variances in level and growth, which represent inter-individual differences in developmental trajectories. For the current purpose, the mean of the intercept is not of interest because the numerical values of the latent ability scale are arbitrarily chosen (see below). The focus is on the increase in children's exploration ability (reflected in the slope) and on the inter-individual differences in developmental trajectories (reflected in the variances of the intercept and the slope). Model building included a second assumption based on IRT, stating that the underlying continuous and developing latent ability can predict the probability of using each form of exploration at a given age and ability level. The higher a child is on the latent ability scale, the greater the chance he or she will display a more complex form of exploration. Using a basic version of a multi-category IRT model known as the graded response model (Embretson & Reise, 2000), mapping the probability of use of a particular exploration form to the latent ability leads to a graphical display as illustrated in Fig. 4. In this figure, the *x*-axis represents the latent ability scale and the *y*-axis represents the probability of engaging in each form of exploration. Individual children as well as group means are assumed to progress on the *x*-axis to the right toward a higher ability level over time. This increase in the latent ability is modeled by the LGM part of the overall model (Boom, 2015).

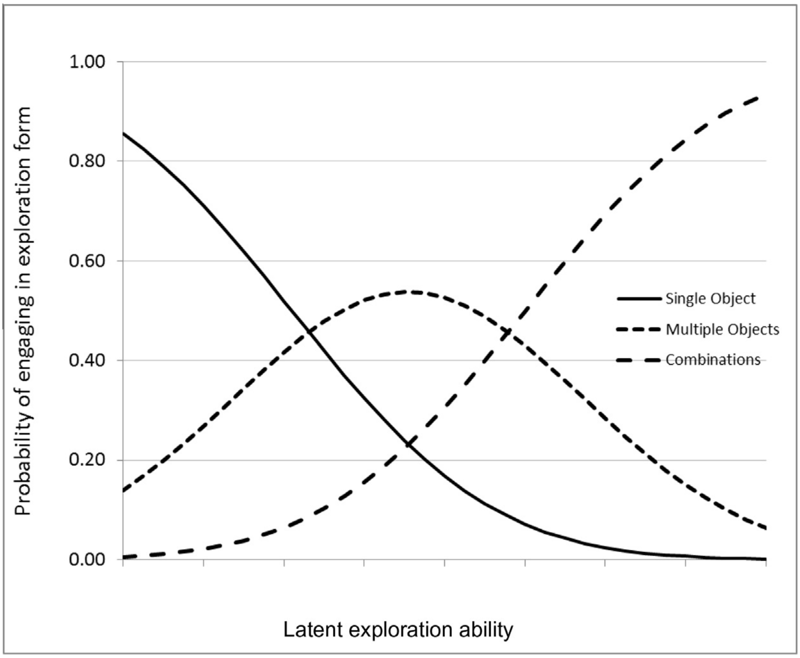


Fig. 4. Overlapping waves model for the development of exploration of spatial-relational properties based on the graded response model. The *x*-axis represents the latent ability that can be scaled in different metrics. The choice of a particular metric is arbitrary. This point is also demonstrated in Fig. 5.

The shape (in terms of steepness) of the curves in Fig. 4 is the same for all curves, and the scale (in terms of location to the right or left) is arbitrary and can be set to a convenient metric (see also Fig. 5). The only parameters to be estimated are the two thresholds that represent the points where the upper and lower curves intersect, the .50 probability level gridline. Together, these two parameters suffice to define the model because they determine the shape and location of the middle curve. More complex models are possible, but the current study opted for the most parsimonious model. The curves of the overlapping waves model were also constrained to remain exactly the same over measurement occasions, reflecting the assumption of measurement invariance over time.

Data from both age cohorts were combined into a single growth model using a cohort-sequential accelerated design. In an accelerated design, data from different age cohorts, drawn from the same population, can be combined on the basis of overlapping measurements to estimate a single growth model, creating a virtual longitudinal cohort that spans the whole age range of the two cohorts together (Duncan et al., 2006). Estimation was done with Mplus Version 7.11 (Muthén & Muthén, 1998–2010; see Example 6.4). The factor loadings and measurement errors of measurements at the two overlapping measurement moments were constrained to be equal in the two cohorts. For the technically interested reader, we provide further details of the modeling approach in the Appendix.

Model fit was evaluated using Bayesian estimation. In this approach, the informative fit statistic is the posterior predictive probability (*ppp*) value, and a *ppp* value of around .50 indicates good model fit. For each estimated parameter value, a credibility interval is computed. For a 90% credibility interval, there is 90% probability that the population value is within this interval (for a detailed explanation, see van de Schoot et al., 2014). We did not specify any informative priors but only used the default priors specified in Mplus (Muthén & Muthén, 1998–2010). If the model fits the observed data well, the *ppp* value should be around .50 and separate curves should arise for each form of exploration, with partial overlap.

Finally, variables were added to the model as predictors of the variances in intercept and slope. Given the small sample size, to limit the number of variables in the model, separate models were

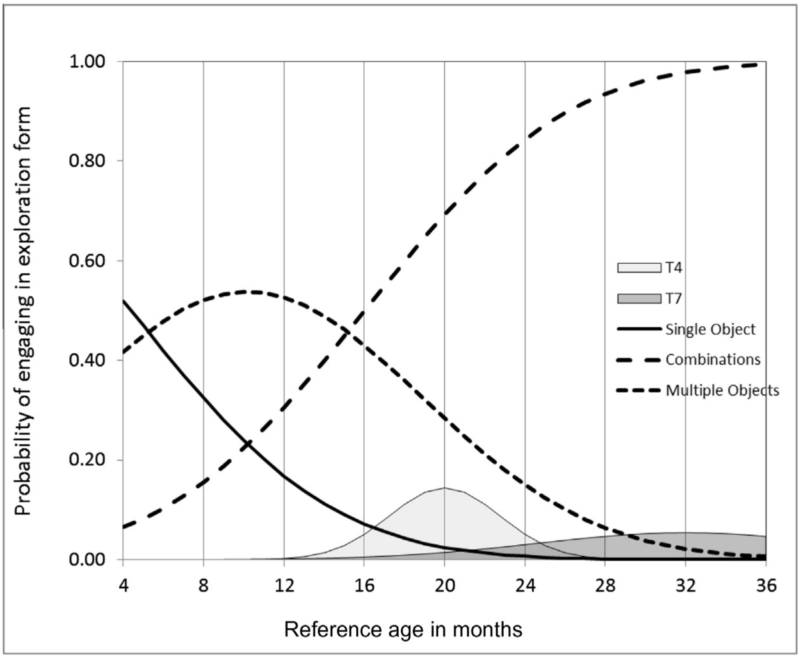


Fig. 5. Overlapping waves model of Fig. 4 now including an indication of the distribution of participants at the fourth and seventh measurements (T4 at 20 months and T7 at 32 months of age) to illustrate growth over this period. The *x*-axis scale represents developmental age: estimated/modeled ability for the average participant at the given age. The distributions (filled areas), therefore, represent individual differences in terms of months ahead of or behind the average.

tested for each predictor. The predictors used were two background variables, gender and SES, and a measure of children's spatial memory at the third measurement moment (16 and 28 months of age for the younger and older cohorts, respectively).

Results

The descriptives of the observation data are presented in Fig. 3 and were already discussed in the Method section. The descriptives for spatial memory and SES are presented in Table 3. This table shows that most parents in the current sample had completed higher vocational or academic education and had jobs at the professional or academic level.

Overlapping waves model

The results of the LGM showed good model fit (*ppp* value = .44). Fig. 5 represents the graded response model shown in Fig. 4, this time using the estimated regression coefficients for each measurement occasion generated by the LGM part of the model. The *x*-axis now represents children's age, thereby relating the scale of exploration skill to developmental age. Moreover, the distribution of participants (as shaded areas) at the first and last measurement occasions was added to aid interpretation of this scale. Note that the *y*-axis scale for these area curves is not the same as for the overlapping waves. However, the shaded area under the curves equals one by definition. These areas are drawn based on assumptions of the Probit model. Given the small sample size, and the resulting error margins, the shape of these two areas must be taken as approximate only. The vertical gridlines in Fig. 5 are spaced such that they reflect the average increase over 4 months (the time distance between

Table 3
Descriptive statistics of model variables.

	M	*SD*
Spatial memory at 16 months	5.63	1.60
Spatial memory at 28 months	7.93	1.05
SES[a]	−0.01	0.78
Education level of mother[b]	6.30	1.02
Education level of father[b]	5.96	1.27
Occupation level of mother[c]	4.05	0.95
Occupation level of father[c]	4.18	0.95

[a] SES is the mean of Z transformations of the scores on parental educational and occupational levels.
[b] Education level was measured on a 7-point scale.
[c] Occupation level was measured on a 5-point scale.

Table 4
Model parameters for overlapping waves model showing the development of exploration.

	Unstandardized value (*SD*)[a]	Standard value	90% CI[b]
Mean slope[c]	.51 (.08)***	–	[.39, .64]
Mean intercept[c]	.00 (.00)	–	–
Variance slope	.08 (.06)***	–	[.02, .21]
Variance intercept	.12 (.14)***	–	[.02, .43]
Covariance intercept–slope	.00 (.00)	.00	–
Factor predicting slope[d]			
Gender	−.28 (.14)*	−.46	[−.53, .06]

[a] SD, posterior standard deviation.
[b] CI, credibility interval around unstandardized parameter value.
[c] Because the scale is arbitrary, standard values for these parameters are meaningless.
[d] Only factors included in final models (after model trimming) are reported.
* $p < .05$.
*** $p < .001$.

measurement occasions). Thus, with each new measurement occasion, children (on average) shifted one gridline step to the right.

Table 4 presents the model parameters. The significant mean of the slope indicates that there is significant development in children's skill to exploit spatial-relational affordances during exploration. As mentioned above, the mean of the intercept (the overall level on the latent scale) is arbitrary and should not be interpreted. The significant variances of both intercept and slope indicate that children vary significantly in both the overall level of exploration skill and the rate of growth over time. The correlation between the intercept and the slope is not significant. Fig. 6 graphically displays the trends implied by the model and the actually observed trends in children's spatial-relational object exploration (created in Microsoft Excel), showing that the model indeed fits the data well given that the lines representing the observed and implied trends largely coincide. Note that Fig. 6 resembles the right part of Figs. 4 and 5, showing the same overlapping waves pattern. Both Figs. 5 and 6 show that, over time, exploration involving single and multiple objects becomes less probable, whereas exploration involving combinations becomes more probable.

Fig. 7 presents a few examples of individual developmental trajectories from the raw data, representing typical cases. The *y*-axis represents the relative frequency of each form of exploration within each observation. Fig. 7A and C show a relatively stable increase of the frequency of combinations and a decrease of the frequency of single object and multiple objects exploration with only small fluctuations. Fig. 7B and D, in contrast, show a less stable pattern. The frequency of combinations, for example, drops and then rises again. Thus, Fig. 7 shows that the growth trajectories of individual children, on which the model is based, indeed show progressions *and* regressions.

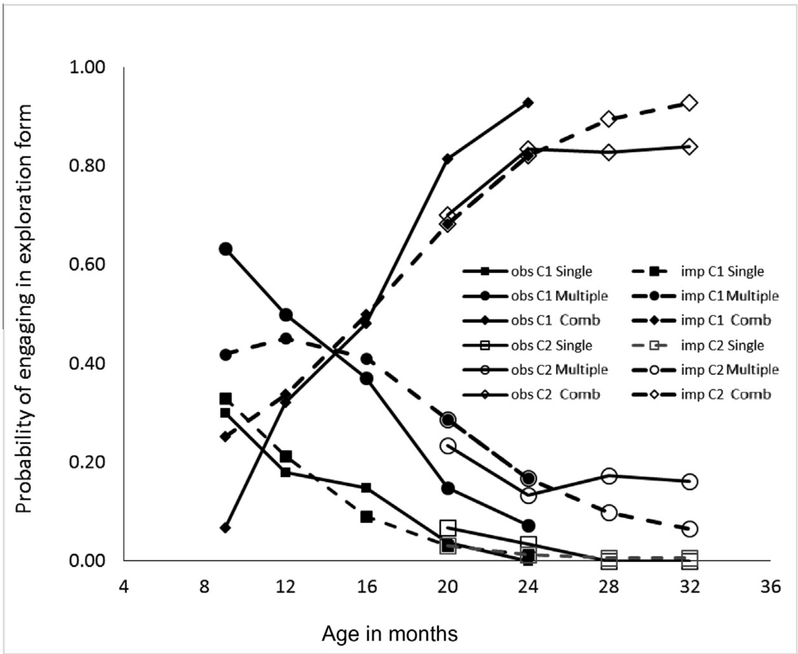


Fig. 6. Observed versus implied trends in children's spatial-relational object exploration from 9 to 32 months of age. obs, observed; imp, implied; C1, younger cohort; C2, older cohort; Comb, combination.

Relations with child characteristics and demographic background

Next, three separate models were built with SES, gender, and spatial memory measured at the third measurement moment (16 months and 28 months of age for the younger and older cohorts, respectively) as predictors of the intercept and the slope. The first model with SES as predictor fitted the data well (*ppp* value = .44) and showed no significant effect of SES on the intercept and the slope. The second model, with gender as predictor, also fitted the data well (*ppp* value = .44). Removal of nonsignificant paths led to similar good fit (*ppp* value = .45) and showed a significant relation between gender and the slope (see Table 4). The effect size is large to medium (R^2 for the slope = .21 for both cohorts). The negative sign of the regression coefficient suggests that girls' exploration skill grows more quickly. Finally, a model with spatial memory as predictor also fitted the data well (*ppp* value = .53). In this model, the best fit was obtained when allowing the effects on the intercept and the slope to vary between the two cohorts. This model did not show significant relations between spatial memory and the intercept and the slope in either cohort. It should be noted, however, that the value of the standard coefficients representing the effects on the intercept ($\beta = .44$) and the slope ($\beta = .37$) appear to be at least medium in size, although they are both nonsignificant ($p > .05$). This situation may indicate a power problem for this particular analysis.

Discussion

The current study examined the development of young children's exploration of the spatial-relational properties of objects within a perception–action theoretical framework. Following Siegler's (1996) theoretical proposal, we could confirm that the development of children's exploration of spatial-relational object properties indeed follows a pattern of overlapping waves. Children progressed from exploring mainly single and multiple objects without combining them toward exploring objects mainly by making combinations using the spatial-relational properties of objects that specify

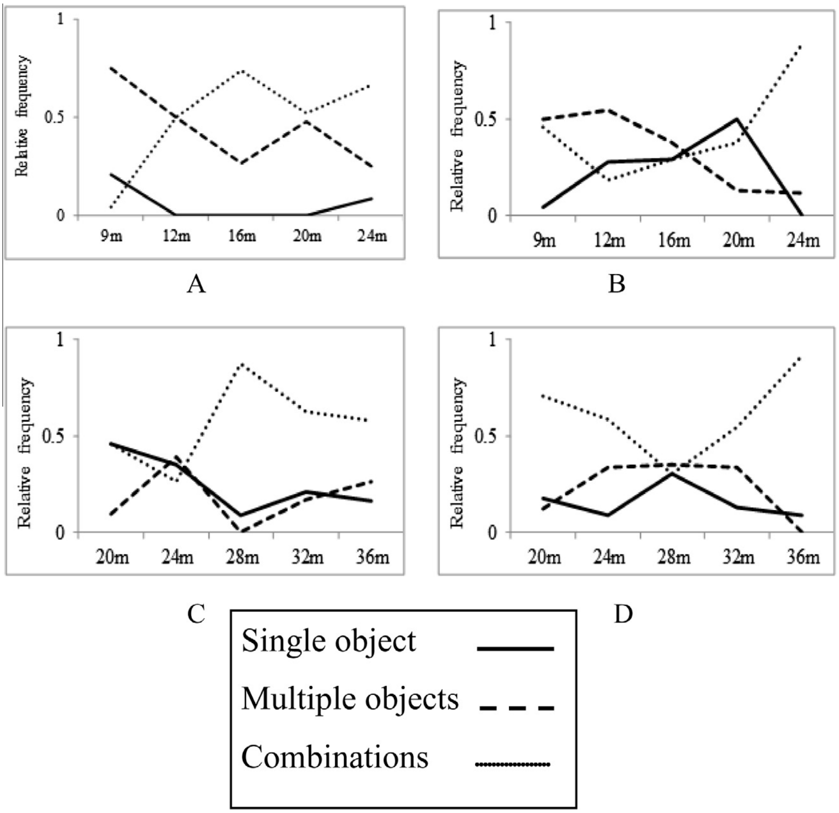


Fig. 7. Examples of individual growth trajectories. (A and B) Trajectories from the younger cohort. (C and D) Trajectories from the older cohort. m, months.

actions such as insertion, pulling out, and stacking. Although with age the probability of engaging in more complex forms of exploration increased, and the probability of engaging in simpler forms decreased, the simpler forms were still observed at later ages. At 36 months, the use of combinations as the main form of exploring the current set of objects was relatively stable. This finding is in line with a perception–action approach viewing development as a dynamic process of becoming increasingly skilled in which the formation of complex skills builds on and is grounded in lower level, simpler skills (Fischer & Bidell, 2006; E. J. Gibson, 1988; Lockman, 2000; Thelen & Smith, 1994).

Our findings are consistent with the findings of Bourgeois and colleagues (2005), who studied the development of exploration of object–surface combinations. Similar to our findings, Bourgeois and colleagues showed in a cross-sectional study that younger children display more single object (or surface) exploration and that older children engage more in object–surface combinations. Furthermore, "less mature" behaviors were still observed in the older children, but less frequently. The current study extends the findings of Bourgeois and colleagues by providing supportive evidence using a longitudinal design. Similar to our results, Belsky and Most (1981), using Guttman scaling, showed that over time more complex play behaviors appear (e.g., functional and symbolic play), but the less mature behaviors still remain present; only the frequency of the behaviors changes. However, the study by Belsky and Most was cross-sectional and based on group means and, therefore, ignored intra-individual variance. Guttman scaling is a deterministic approach, whereas IRT is a probabilistic approach (Hays, Morales, & Reise, 2000), meaning that, in combination with the cross-sectional data, this approach cannot account for regressions in development (which are treated as measurement errors). Finally, Belsky and Most (1981) treated exploration as stage within play development, with functional and finally symbolic play as the most advanced forms. However, as discussed in the Introduction, within a perception–action approach, exploration and functional and symbolic play cannot be seen as part of the same skill.

The current study shows that children's exploration of spatial-relational object properties over time can be represented on a "latent ability" scale. A question is what the latent scale actually measures and to what extent the common (statistical) notion of *latent* is applicable. We suggest that the latent growth factor in our model is actually a measure of children's *observable* increasing skill to pick up and exploit the spatial-relational affordances of (constellations of) objects. Although it is tempting to interpret the observed growth as an internal ability that matures with age, we propose, in line with the perception–action framework, that it rather represents children's increasing skill to perceive and act on what is there in the environment. The developmental process of becoming increasingly skilled cannot be reduced to mere bodily growth and motor development. Although this process is obviously constrained by children's maturing physical possibilities and neuromuscular motor maturation, the development of exploration skill is primarily driven by both children's continuously recurring engaged exploration, on the one hand, *and* the information structures available for them in the environment, on the other (see also Greaves et al., 2012). In the current study, the available information structures were the spatial-relational properties of the particular set of objects that was presented to the children.

The pattern of overlapping waves that was observed contributes to the understanding of intra-individual variability in development. Temporary regressions (behavior of a previous stage is observed) constitute a well-known problem for stage theories of development because of the assumption that once a child has reached a certain stage all behavior should conform to the epistemological constraints of that stage (see van Geert & van Dijk, 2002). The use of newly developed statistical techniques enabled us to account for this intra-individual variability in the development of spatial-relational object exploration. Because the different forms of exploration are interdependent (i.e., only one form can be present at a given moment), they were regarded as outcomes of the same variable representing the continuously developing skill in exploiting spatial-relational affordances. The overlapping waves model, then, enabled us to model regressions and progressions in this skill. The current results, in line with the perception–action account, suggest that the observed use of more simple forms of exploration should be regarded as an indication that later developing, more complex skills still build on earlier developing, less complex skills (Fischer & Bidell, 2006; Lockman, 2000). For example, the discovery of the complex spatial-relational affordance of stacking objects in a multiple objects constellation requires the perception of the elementary affordances of single objects (e.g., flat solid surface) first. We propose that becoming skilled means becoming increasingly skilled at very rapidly discovering and using the elementary affordances of objects, which then opens the possibility of discovering affordances that specify more complex actions.

We further examined relationships of the observed exploration development with child and demographic background characteristics. We found, a relation with gender, suggesting that, girls' exploration skills with this set of objects grows more quickly than boys' exploration skills. Previous work (e.g., Pomerleau & Malcuit, 1992; Servin, Bohlin, & Berlin, 1999) has also shown gender differences in exploratory behavior from an early age. Girls, for example, were shown to engage more than boys in pinching and object displacement. These studies, however, did not examine gender differences in exploration of spatial-relational properties of objects as in the current study. Early differences in exploration behavior are definitely worth discussing, especially given the link between exploration and spatial abilities (Oudgenoeg-Paz et al., 2015). Gender differences in spatial abilities such as mental rotation are often reported (e.g., Newhouse, Newhouse, & Astur, 2007; Spetch & Parent, 2006). However, there is still much discussion regarding the age at which these differences emerge (Levine et al., 2005) and the nature of abilities affected by such differences (e.g., Alloway, Gathercole, & Pickering, 2006; Robert & Savoiea, 2006, suggest lack of differences in visuospatial memory). The results of the current study seem to suggest that at an early age a slight advantage for girls can be seen in the extent to which they explore spatial-relational object properties. However, given the small sample size, replication is required before any definitive conclusions can be drawn.

No significant relations were found between exploration skill and SES. A likely explanation is the restricted variance in SES in the current study. The vast majority of children in the current sample came from middle- to high-SES families. Contrary to the hypothesis, no significant relations were found between exploration skill and spatial memory. Spatial memory was measured at 16 months in the younger cohort and at 28 months in the older cohort. A likely explanation for the lack of relations at 28 months is that at that age the variance in exploration skill in the older cohort was relatively small (i.e., most children score high; see Fig. 5). Thus, for this cohort, the variance to be explained was much smaller. The lack of relation between exploration skill and spatial memory in the younger cohort, however, is surprising. Still, the size of the standard coefficients suggests that the power of this analysis might be too low. Therefore, no definite conclusions can be drawn from this relation. Previous research with the same sample has shown that spatial-relational exploration at 20 months of age is related to spatial memory at 24 months of age (Oudgenoeg-Paz et al., 2015). Moreover, a different study showed long-term relations between spatial exploration during infancy (defined as exploration of spatial relations between objects, as in the current study, and exploration of the larger space through self-locomotion) and spatial memory at school age (Oudgenoeg-Paz et al., 2014). However, both of these studies used measures of spatial memory that are somewhat different from the measure used in the current study. The tasks used in these studies placed higher demands on executive functions. For example, in the study of Oudgenoeg-Paz and colleagues (2014), children needed to remember the location of a dot in a matrix. But rather than remembering the location of a single dot, they were required to remember several locations at once. It might be that performance on these more complex tasks is more strongly linked to spatial-relational object exploration than performance on the simple task used in the current study. Future work will need to further test the construct validity of the model by replicating this analysis using a larger sample and by testing the hypothesis regarding the different relations with the different tasks used to measure spatial memory.

Given the composition and small size of the sample, the results of the current study should be interpreted with caution. More research is needed to further examine the generalizability and validity of the model developed in the current study. Future research could investigate the exploration of spatial-relational object properties as a predictor of future abilities as well as extend the current work by focusing on other aspects of spatial-relational exploration such as the complexity of the combinations made in terms of the different types of relations explored. Extending the current approach to other kinds of spatial exploration behavior, such as exploration of larger spaces through self-locomotion, is also recommendable. Another interesting direction for future research would be to examine more closely the dynamics of exploration at the micro level, that is, the development of exploration skill within a given task. Micro-level research can reveal whether similar developmental patterns as found in the current macro-level study characterize microdevelopment, with changes from more simple to more complex forms of exploration from the beginning toward the end of a task. This can contribute to the understanding of the relationships between developmental processes taking place on different time scales (see van Geert & Steenbeek, 2005, for a discussion of the relations between development on the micro and macro time scales). Finally, the current study proposed two basic driving forces of individual development: engagement in exploration and information structures in the environment. If these factors are indeed driving forces in development, examining individual differences in engagement and basic personal characteristics underlying engagement, such as temperament, is a highly relevant research topic. In addition, individual differences in the available information structures, such as in the form of play materials and opportunities to explore these materials, are another relevant research topic. Future studies should examine the effects of relatively impoverished versus enriched environments on development of exploration, as related to the family's SES or to the quality of the day-care provision used.

A clear limitation of the study was the relatively small sample size. This had consequences for the power of the study. This limitation was partially compensated for by the multiple measurement moments employed in the study, increasing the total number of data points, and by the use of a sequential cohort design, increasing the degrees of freedom of the model (Duncan et al., 2006). In addition, Bayesian estimation was used to assess model fit. This method is suitable for small samples because it increases the confidence in the parameter estimations obtained with small samples (van de Schoot et al., 2014). Finally, the use of children's home environment as the setting in which to conduct the observations offered less possibility for standardization and control. However, due to the choice to conduct the study at children's homes, the current study can be considered ecologically more valid than other studies on exploration and spatial development that used lab settings. Coding in fragments of 10 s is arbitrary and carries the risk of under- or overestimating certain actions. However, because the exploration forms coded in the current study do not necessarily systematically differ in length (i.e., single object exploration is not always shorter or longer in duration than exploration using combinations), it seems reasonable to assume that any measurement error caused by this choice is not systematic. It is also important to note that in the current study the development of exploration skill was coded in terms of complexity of the skill rather than in terms of the content (the specific actions done with the objects). Thus, the displayed level of exploration is clearly dependent on the specific context (i.e., the objects that children were presented with), whereas the coding itself is relatively content independent and, therefore, can be applied to other contexts (i.e., using other constellations of objects) as well (see also Fischer & Bidell, 2006).

The current study contributes to the knowledge of child development in both theoretical and methodological respects. First, the current findings support a perception–action approach to development by showing that the development of more complex spatial-relational object exploration skill builds on and is grounded in less complex spatial-relational object exploration. Second, children in the current study varied substantially in both their overall level of exploration skill and the rate of growth, suggesting that group averages are not always the best representation of the developmental process. Work focusing on individual trajectories is a promising method to gain insight into various developmental mechanisms. Finally, the study contributes to the repertoire of analytical methods for research in child development by showing the feasibility of combining latent growth modeling for categorical data with assumptions of item response theory to model development as a series of overlapping waves, as suggested by Siegler (1996), Boom (2015), and van der Ven and colleagues (2012). This approach can be a powerful tool for studying development over multiple measurement moments because it can account for the general level of an ability or skill, the average developmental trajectory of a particular sample, the inter-individual differences in developmental trajectories, and the frequently observed intra-individual variability in development. Individual differences in the parameters of a model as used in the current study can be examined and related to other characteristics of the child and the environment, and the parameters can be used to predict future skills in domains such as spatial cognition, language and social–emotional competence.

Appendix

Model building

The constructed model was a latent growth model with categorical data. In addition, because the current study applied a cohort-sequential design, a two-group model was used to combine data from the two age cohorts. For the two-group model, a mixture analysis with known classes needed to be used; for the categorical part of the model, a Probit link was used. The Bayesian estimator was used because it performs better with small samples and, in particular, the distribution of variance parameter estimates is more accurate (van de Schoot et al., 2014). The scale for the overlapping waves model was chosen such that children's scores at the fourth measurement point (midpoint in age) are distributed around the zero point on the x-axis (which, thus, represents the average ability at 20 months of age). This was done by setting the loading of the fourth measurement point on the slope to zero. This anchor point was chosen because, in the LGM part of the model, this choice led to minimal slope–intercept covariance. Being able to eliminate this covariance (due to its not being significant) makes interpretation of the slope more straightforward. To be able to display the person distributions in Fig. 5, the shape of these distributions was smoothed.

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