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Getting the big picture: Development of spatial scaling abilities

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ABSTRACT

Spatial scaling is an integral aspect of many spatial tasks that involve symbol-to-referent correspondences (e.g., map reading, drawing). In this study, we asked 3–6-year-olds and adults to locate objects in a two-dimensional spatial layout using information from a second spatial representation (map). We examined how scaling factor and reference features, such as the shape of the layout or the presence of landmarks, affect performance. Results showed that spatial scaling on this simple task undergoes considerable development, especially between 3 and 5 years of age. Furthermore, the youngest children showed large individual variability and profited from landmark information. Accuracy differed between scaled and un-scaled items, but not between items using different scaling factors (1:2 vs. 1:4), suggesting that participants encoded relative rather than absolute distances.

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The ability to reason about objects in space and to represent spatial layouts is an important aspect of everyday cognition, with evolutionary and adaptive importance. Any mobile being must represent its position with respect to the spatial environment to be able to navigate in its world. In addition, the human species has a unique ability to devise tools and technologies to help meet these cognitive challenges. For example, maps and global positioning systems (GPSs) help to represent spatial relations and configurations. Such navigational tools usually depict small-scale two-dimensional representations of parts of the referent space. In order to understand and interpret these spatial representations, we must understand that they are miniaturized (and often arbitrary and symbolic) versions of their large-scale counterparts. In addition, we must be able to scale the spatial information provided by the

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representations in order to apply it to the referent space. *Spatial scaling*, or the ability to transform distance information from one representation to another one of a different size thus constitutes an integral component of map reading, navigation and other spatial tasks that involve representational systems. Moreover, spatial scaling may be a spatial ability important for success in science, technology, engineering and mathematics. Wai, Lubinski, and Benbow's (2009) analysis of a large longitudinal data set focused on mental rotation and other abilities assessed in traditional paper-and-pencil tests, but we must also consider the scaling demands of the sciences. For example, an engineer may interpret a blueprint of a large building, a geoscientist may use a sketch to visualize the processes that led to the formation of the earth, an astronomer may study a Hubble Ultra Deep Field Image of the universe, and a science text may map the structure of a solar system onto a model of an atom.

In developmental research, spatial scaling has often been investigated in the context of map-reading skills (e.g., Liben & Downs, 1994; Uttal, 1996, 2000). However, interpreting maps requires a number of additional spatial competencies (Liben & Downs, 1994). In order to comprehend maps and to be able to use them effectively, one must understand (a) the correspondence of the symbols on the map to their referents, (b) the orientation of the map and how to align it with the referent space if necessary, (c) the viewing angle of the map – for example whether it represents a space from an overhead view, (d) how a three-dimensional space is projected onto a two-dimensional one and (e) the viewing distance, that is, the scale of the map, and how to relate distances on the map to those in the referent space. The present study focuses on the last competency – the ability to scale distances, aiming to assess its development distinct from the other four competencies.

Research on symbol-referent correspondence has shown that children as young as 3 years have a basic understanding of symbolic relations between maps or scale models and large-scale referent spaces (DeLoache, 1987, 1989, 1991). Similarly, young 3-year-olds are able to locate a target object in a larger room after seeing the corresponding location in a model (Blades & Cooke, 1994). However, this ability appears to be restricted to unique hiding places. When the hiding place was one of two identical places (e.g., under one of two identical-looking chairs), such that spatial relations had to be taken into account, it was not until 4 years of age that children succeeded. When a hiding place is unique, children may solve the task by associating a symbol with the hidden object and establish symbolic or 'representational' correspondence (Liben & Yekel, 1996). However, spatial or 'geometric' correspondence (Downs, 1985) is necessary to link spatial properties of the referent space with spatial features of a map or model.

According to Liben and Downs (1994), extracting spatial information and understanding geometric properties of a map rely on a basic understanding of projective spatial concepts, as described by Piaget and Inhelder (1948/1956). In their seminal work on *The Child's Conception of Space*, Piaget and Inhelder distinguished between *topological, projective and Euclidean* space. They proposed that *topological* space was "psychologically primitive" and referred to intrinsic properties internal to the figure/object. Between approximately 4 and 7 years of age, basic spatial concepts such as proximity, separation, order, enclosure, and continuity characterize children's spatial representations, so that, for example, a drawing of a human face will place the eyes close to each other and inside the boundary of the head. An understanding of topological space may be sufficient for establishing symbolic correspondences and for solving map tasks with unique hiding places, if the object's location can be determined by means of remembering enclosure, or proximity to a specific landmark. An understanding of *metric* and *projective* space, however, is necessary for locating objects relative to one another and in accordance with general perspective or projective systems. According to Piaget and Inhelder, it is not until after 7–8 years of age that children's spatial representations begin to reflect distances and proportions, or that they recognize two rectangles of different sizes but equal proportions as having the same shape.

In line with these theoretical accounts, research has shown that extracting spatial information from representations is difficult for young children (Liben & Downs, 1993; Uttal, 2000). Using a task that required placing stickers on a map to indicate the location of objects in their classrooms, Liben and Yekel (1996) found that 4–5-year-olds had considerable difficulties understanding geometric and even representational correspondences. They had troubles interpreting maps even when the task involved a highly familiar room, the map was presented simultaneously and in alignment with the referent space, and the task required the identification of only a single location at a time.

In other research, children's interpretations of maps or models were investigated by having them reconstruct a represented spatial layout. For instance, Uttal (1996) asked 4- and 5-year-olds to reconstruct configurations of six objects in a room, after having memorized a smaller map depicting the locations of the objects. Even though most children preserved the overall configuration of the objects, their reconstructions were often too small, suggesting that they did not compensate for the smaller scales of the maps. But even in studies that did not involve maps, and thus did not require a translation in dimensionality, preschoolers struggled with scale transformations. For example, Liben, Moore, and Golbeck (1982) asked 3–5-year-olds to reconstruct the layout of their familiar classroom using either a model or life-sized furniture. Performance was significantly better with life-sized furniture that did not require scale transformations than with a model, even though no memorization of the layout was necessary. Thus, various studies suggest that children between ages 3 and 5 have considerable difficulties with scaling tasks, as well as with other components of map use. It is not until about 7 years of age that children begin to be successful on aligned map tasks that require an understanding of both scale and spatial layout of a map (Liben & Downs, 1993).

However, in seeming contradiction to research on young children's difficulty extracting spatial information from maps and models, research using very simple tasks has suggested that the ability to scale distances can be observed quite early. For instance, Huttenlocher, Newcombe, and Vasilyeva (1999) showed that all of the 4-year-olds and about half of the 3-year-olds tested were successful at translating distances from a map to find an object hidden in a larger sandbox, if they only had to locate one object along a single dimension (i.e., if target locations were distributed along the horizontal axis in a narrow rectangular sandbox). Huttenlocher, Vasilyeva, Newcombe, and Duffy (2008) confirmed that the ability to use spatial information provided by a small model to retrieve a target object in a narrow sandbox emerges at roughly 4 years, although success varied as a factor of task format. Specifically, children were successful half a year earlier on average when a physically present object was to be placed using a map, as opposed to using the map to retrieve a hidden object.

Huttenlocher et al. (1999) proposed that toddlers succeed in their scaling tasks, long before they are successful in proportional reasoning tasks, because they use a perceptual strategy to relate visible distances to one another. That is, they may encode the relative distances of the target from the left or right edge of the map, rather than encoding absolute distances. This type of relative coding preserves the relation between distances even if applied to spaces of varying size. Coding absolute distances is more difficult, because those distances need to be transformed when applied in a different size space, which may require proportional thinking. Thus, the early ability to establish location may be restricted to enclosed spaces, in which distances are perceptually available and can be related directly without imposing measurement units.

In terms of scaling tasks that involve two dimensions (i.e., with target locations distributed along both an x- and a y-axis), Vasilyeva and Huttenlocher (2004) found that approximately 60% of 4-year-olds and 90% of 5-year-olds succeeded in placing objects on a rectangular rug based on information from a smaller map. Thus, children succeeded about a year later in the two-dimensional situation than when only one dimension had to be considered. Similarly, in a study requiring children to place an object into one of three containers in a rectangular room according to a marked location on a simple map, 4-year-olds were able to detect geometric correspondence (Shusterman, Lee, & Spelke, 2008). Children used and encoded geometric information in the maps even without specific task instruction or feedback, and the presence of a distinctive landmark facilitated overall performance.

Overall, these findings may not be contradictory. Rather, they likely indicate a developmental sequence. Spatial scaling abilities develop considerably during the preschool years, beginning at 3 years of age following the establishment of basic representational correspondence. At this point, at least some children are able to use spatial information provided by small maps or models and apply this knowledge to larger spaces. However, this achievement occurs only under ideal circumstances and if task demands are low (e.g., if the task involves only one dimension and does not demand additional spatial transformations), and it likely involves perceptual coding of relative distance. By age 4, children are mostly successful at scaling along a single dimension but still show great variability on two-dimensional scaling tasks. Performance varies as a function of task specifics, such as whether landmarks are available or whether objects have to be placed or retrieved. By approximately age 5, children's spatial mapping skills become more flexible, and they begin to succeed in placement tasks

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that involve two dimensions. However, performance is still far from perfect at age 5, and it is not until around age 7 that the developmental trajectory begins to level out. Accepting this conclusion, however, requires amalgamating the results of a variety of studies, which vary in multiple ways.

The present study aimed to establish a developmental sequence within this age range using a single method. Data from adult participants were gathered additionally, in order to establish a benchmark of "mature" performance. We created an instrument that could be used to chart the development of scaling, thereby eliminating factors that varied across previous studies and might have accounted for difficulties older children exhibited in some tasks. The basic task was to locate hidden objects (eggs) in a two-dimensional referent space (fields on a farm) using spatial information presented on a map. Several task features were designed to reduce cognitive demands and thus investigate the developmental trajectory of spatial scaling ability independently from other skills necessary for map reading. First, the referent spaces and maps were aligned and in the same viewing angle, obviating the need for mental transformation (other than scaling) to compare them. Second, referent spaces and maps were both presented two-dimensionally, so no dimensional translation was required. Third, referent spaces and maps were presented simultaneously, obviating the need for memorization. Lastly, a placement method was used, based on findings (Huttenlocher et al., 2008) that placement tasks are sometimes easier for young children than retrieval tasks.

We also systematically manipulated a number of variables that, according to previous results, are likely to affect spatial scaling performance. One dimension of variation was the spatial features that may be used as reference points to locate the object. Hiding spaces and corresponding maps either had boundaries that extended mostly in one dimension (narrow strips) or in two dimensions (rectangular fields), or they provided landmarks as reference points (with featureless circular boundaries). Based on previous research, we expected at least some children to be able to scale distances on narrow strips at age 3, good performance on narrow strips by age 4, and better performance on rectangular layouts that extended in two dimensions by age 5. Furthermore, we expected better performance with landmarks, because they may promote the use of associative strategies based on proximity. We targeted an age range from 3 to 6 years to cover this expected developmental progression.

A second dimension of variation involved scaling factor. This manipulation had the objective of shedding light on children's strategy choices and cognitive mechanisms. If children solved our scaling task by coding absolute distances and then transforming them by the scaling factor – or if they failed to scale the distances entirely – we expected larger errors for larger scaling factors (Vasilyeva & Huttenlocher, 2004). If, however, children used a more perceptual or holistic strategy that accounts for overall relative distances, scaling factor should be of less importance. Some trials that did not require scaling were included to provide baseline information on how well children can use information from one representational space and apply it to another, regardless of scaling abilities.

1. Method

1.1. Participants

Eighty children participated, 20 (10 girls) in each of four age groups: 3-years-olds (mean age = 40 months, range 36–47 months), 4-year-olds (mean age = 52 months, range 48–59 months), 5-years-olds (mean age = 65 months, range 60–71 months), and 6-years-olds (mean age = 77 months, range 73–81 months). Three additional children were tested but excluded from analyses due to lack of task comprehension (one 3-year-old), or incomplete data (one 3-year-old and one 4-year-old). The sample was predominantly middle class and racially mixed and was recruited in urban and suburban areas of a large US city. All children spoke English and were tested in English. Additionally, 12 adults were tested (mean age = 23 years, range 19–31 years, 6 females); this group consisted of psychology students at undergraduate through post-doctoral levels.

1.2. Stimulus material

Color drawings of three different green "fields" (Fig. 1a–c) were mounted on black letter-sized paper (centered and in landscape orientation) and presented in document pockets inside a 3-ring

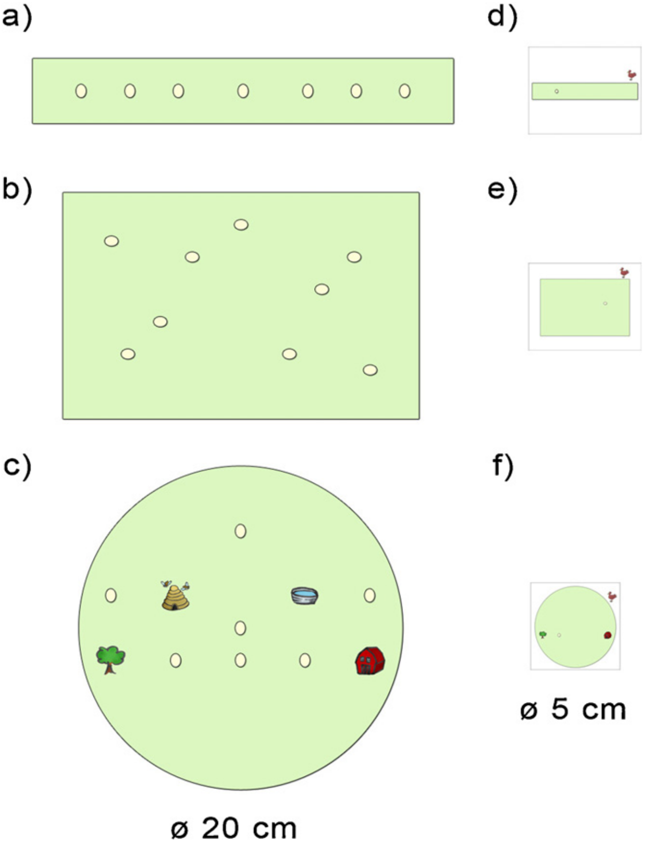

Fig. 1. Examples of the three hiding spaces ("fields") with different reference features: (a) strip, (b) rectangle, and (c) circle with landmarks. All possible egg locations are shown here, but the presented stimulus fields did not show any eggs and maximally two landmarks. Examples of maps (scaling factor 1:4) are shown to the right of each filed (d–f).

binder. One type of field was rectangular in shape (22 cm long and 14 cm wide), and thus extensions along two dimensions had to be taken into account. Another type of field was long and narrow (26 cm long and 4 cm wide), henceforth referred to as 'strip'. A third type of field was presented to investigate how participants use landmark information as reference points. In order to minimize geometrical information, the boundaries in this case were circular (with a 20 cm diameter). Fig. 1c shows all possible presented landmarks (tree, beehive, tub, and house); only two landmarks were shown simultaneously. Fig. 1a–c also illustrates the spatial distributions of all possible target locations in the different fields. The rectangles and circles had an area of 308 cm^2 and 314 cm^2, respectively, and were thus comparable regarding size; the strips had an area of 104 cm^2. The sizes of these hiding spaces were held constant across trials of different scaling factors.

Each field was presented along with a map (Fig. 1d–f). The map showed the same field, with an egg on the field and a chicken outside the field in the upper right-hand corner. Maps were either un-scaled (1:1) or scaled according to one of two scaling factors (1:2 or 1:4). For scaling factor 1:1, maps had the same size as the hiding spaces; for scaling factor 1:2, every distance on the map corresponded to twice the distance in the hiding space – as a consequence, the area of the hiding space was 4 times larger; for scaling factor 1:4, every distance on the map corresponded to a four times larger distance in the hiding space, and the area of the hiding space was 16 times larger. Scaling factors were manipulated between maps rather than between hiding spaces, in order to guarantee a constant level of error variance in responses and in precision of measurement across different scaling factors.

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Participants used a small rubber peg to locate the eggs on the fields. A suction cup at the bottom of the peg prevented it from toppling over or moving and allowed for precise recording of the responses. The peg was 29 mm long, the bottom end of the peg had a diameter of 7 mm, and the grip had a diameter of 5 mm.

1.3. Procedure

Participants were tested in a separate room at their schools or in the laboratory. The materials were presented on a table, with the experimenter seated orthogonally to the right of the participants. The first page in the binder presented a cartoon of a farmer, a chicken and some eggs. This cartoon was used to illustrate a short story about Farmer Fred, who had a big farm with many chickens and different fields. The experimenter told the children that the chickens hid their eggs in the fields every morning when Farmer Fred wanted to collect them and asked the children to help Farmer Fred find the eggs. Next, children were shown a field and told that the first chicken hid her egg somewhere in this field. Then a map was placed directly to the right of the field and children were told that this picture showed where the chicken hid her egg and that the egg would be in the same place in the field. Children were then asked to put the peg on the field where they thought the egg was hidden.

After each response, the experimenter marked the position of the peg with a fine-tip wet-erase marker, flipped the page, and presented the field and map for the next trial. Maps that were not in use were kept out of sight. Participants did not receive feedback about the correctness of their responses. The experiment consisted of 25 trials and lasted approximately 10 min. After the experiment, all of the responses were copied onto a transparency, scanned, and recorded in terms of *x*- and *y*-coordinates rounded to the nearest millimeter. Data sets of 20 participants (4 of each age group) were re-coded by a second naïve experimenter. Pearson's correlation between measurements of the two experimenters was $r = .998$.

1.4. Design

Trials varied according to scaling factor (1:1, 1:2, or 1:4), reference features (strip, rectangle, or circle with landmarks), and hiding location. To make results more comparable on an individual level, trials were presented in a standardized order. We presented a 1:1 trial first as a warm-up and baseline, followed by three 1:4 trials for the strips (Trials 1–4), rectangles (Trials 5–8), and circles with landmarks (Trials 9–12). Three 1:2 trials for each type of field were presented last (Trials 17–25) for three main reasons. First, we attempted to present trials in order of increasing difficulty, and because for 1:4 trials it is more obvious that distances have to be scaled, it may be easier for young children to understand what the task is. Second, for 1:4 trials it is easier to differentiate systematic variance in scaling accuracy from unsystematic error variance, and thus 1:4 trials are more informative than 1:2 trials. Third, we were concerned that young children might not finish all 25 trials – fortunately, this only happened for two children whose data were excluded.

In the middle of the experiment (i.e., as Trials 13–16), four slightly different trials were included to disrupt automatic responding and to keep children engaged. These trials will not be discussed further.

Two versions of the task were implemented to counterbalance for possible left–right response biases. Each version was presented to approximately half of the participants of each age group and gender. For every hiding location in Version A, Version B contained a symmetrical hiding location. For example, in Trials 2 through 4 of Version A, the eggs were hidden at 9 cm from the *left* edge, 6 cm from the *right* edge, and 3 cm from the *left* edge of the strip, respectively. Conversely in Trials 2 through 4 of Version B, the eggs were hidden at 9 cm from the *right*, 6 cm from the *left*, and 3 cm from the *right* edge. The side of the hiding location was alternated from trial to trial to prevent children from directly comparing with previous trials. For rectangles, e.g., in Trial 7A, the egg was hidden 3 cm from the *left* and 3 cm from the *top* edge of the rectangular field; in Trial 7B it was hidden 3 cm from the *right* and 3 cm from the *bottom* edge. For circles, e.g., in Trial 10A, the egg was at 1/4 the distance (3 cm) from the *tree* to the *house*; in Trial 10B it was at 1/4 the distance from the *house* to the *tree*.

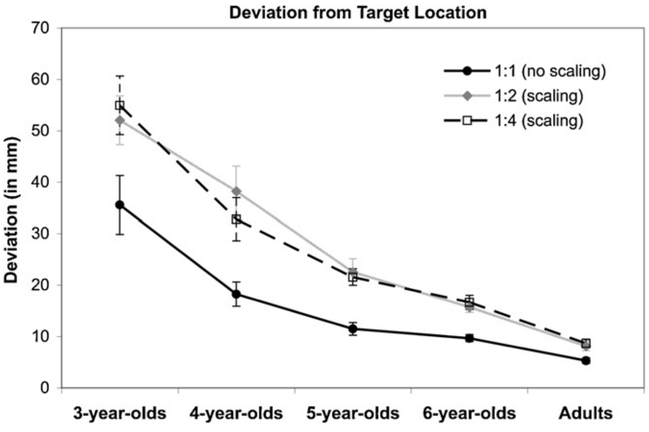

Fig. 2. Mean absolute deviations from target locations (in mm) by age group and scaling factor. Error bars represent standard errors of the means.

2. Results

2.1. Absolute deviation on the group level

In order to investigate participants' accuracy on this spatial scaling task, the deviations of their responses from the target locations were analyzed as absolute distances in millimeters. As a measure of lower bound to the reliability, Guttman's Lambda 2 (λ_2, Guttman, 1945; see also Sijtsma, 2009) was calculated on the basis of the absolute deviations on all 25 items and showed a good reliability of $\lambda_2 = .92$ for the total sample. Separate analyses showed that reliabilities for the 3-year-olds, 4-year-olds, and adults were good ($\lambda_2 = .85$, .86, and .86, respectively), although reliabilities for the 5- and 6-year-olds were moderate ($\lambda_2 = .75$ and .70, respectively).

We compared the absolute deviations of participants' responses from the target locations using analyses of variance (ANOVA). A preliminary ANOVA including the between-subjects variable of version (A and B) yielded no effects or interactions involving version, all *ps* > .15, all $\eta^2 < .08$, and therefore this variable is not considered further.

An ANOVA was performed with absolute deviation from target as the dependent variable, the within-subject variables of scaling factor (1:1, 1:2, 1:4), and reference features (strip, rectangle, circle with landmarks), and the between-subjects variables of age group (5) and sex (2). Results showed a significant main effect of age, $F(4, 82) = 31.20$, $p < .001$, $\eta^2 = .60$ (Fig. 2). Post hoc tests (Tukey HSD) showed a significant decrease in absolute deviation between 3- and 4-year-olds (mean difference = 17.76, $p < .001$) and between 4- and 5-year-olds (mean difference = 11.21, $p < .05$), but no reliable difference between 5- and 6-year-olds (mean difference = 4.51, $p = .75$) or between 6-year-olds and adults (mean difference = 6.66, $p = .54$). As seen from the standard deviations in Table 1, inter-individual differences

Table 1
Mean absolute deviations from target locations (in mm) per age group, scaling factor, and reference features, including overall group means and standard deviations (*SD*).

Age group	Scaling factor			Reference features			Mean	*SD*
	1:1	1:2	1:4	Strip	Rectangle	Circle with landmarks		
3-Year-olds	35.57	52.03	54.93	58.15	55.30	39.30	50.92	20.48
4-Year-olds	18.24	38.21	32.78	34.72	41.06	23.31	33.03	16.36
5-Year-olds	11.48	22.54	21.57	18.81	27.61	15.22	20.55	6.66
6-Year-olds	9.68	15.74	16.65	14.61	19.20	11.99	15.27	4.16
Adults	5.30	8.15	8.64	8.02	10.49	5.34	7.95	2.56

decreased with age, with the 3- and 4-year-old groups showing especially large variance. The analysis yielded no main effect of sex, $F < 1$, but sex interacted with age group, $F(4, 82) = 2.51$, $p < .05$, $\eta^2 = .11$. Group means suggest that this interaction was mainly due to 3-year-old boys producing larger deviations ($M = 54.54$ mm, $SE = 3.75$) than 3-year-old girls ($M = 40.48$ mm, $SE = 3.75$). However, separate analyses of each age group showed that the effect of sex was not statistically significant for any of the age groups, all $ps > .12$.

Furthermore, the ANOVA yielded a significant main effect of reference features on participants' absolute deviations, $F(2, 164) = 32.75$, $p < .001$, $\eta^2 = .29$, and an interaction of reference features and age group, $F(8, 164) = 3.92$, $p < .001$, $\eta^2 = .16$. Table 1 shows that all age groups performed best on trials with circular boundaries and landmarks. Pairwise comparisons (Bonferroni corrected) confirmed that all age groups were significantly more accurate on circles with landmarks than on rectangles (all $ps < .01$). Adults, 4-year-olds, and 3-year-olds were also more accurate on circles with landmarks than on strips (all $ps < .05$), although the 5- and 6-year-olds were not (both $ps > .10$). Although 3- and 4-year-olds showed no significant differences between strips and rectangles (both $ps > .12$), all older age groups performed significantly better with strips than with rectangles (all $ps < .05$).

Finally, the ANOVA showed that scaling factor had a significant effect on participants' absolute deviations, $F(1, 164) = 33.61$, $p < .001$, $\eta^2 = .29$, and interacted with age group, $F(8, 164) = 2.65$, $p < .01$, $\eta^2 = .12$. All other effects and interactions were non-significant, all $ps > .28$, all $\eta^2 < .06$. Fig. 2 suggests that participants performed better on trials that did not require scaling than on those that did require scaling, and this difference decreased with age. Pairwise comparisons (Bonferroni corrected) confirmed that all age groups were significantly more accurate on un-scaled (1:1) than on both 1:2 scaled and 1:4 scaled trials (all $ps < .05$); however, there was no significant difference in any of the age groups between 1:2 and 1:4 scaled trials (all $ps > .66$). All above-mentioned non-significant pairwise comparisons remained non-significant even if a more sensitive correction for multiple comparisons (Least Significant Difference) was applied instead of the conservative Bonferroni correction. This suggested that the main effect of scaling factor was not due to differences between maps scaled by different factors, but to differences between un-scaled and scaled maps. This general pattern was the same for all age groups, but the interaction of scaling factor and age group indicated that the differences between un-scaled and scaled maps decreased with age.

2.2. Signed errors on group level

Whereas absolute deviations allow for analyses of average accuracy, they yield little information on the nature and direction of children's errors. An inspection of the direction of children's errors and their relative accuracies can serve to identify response strategies and spatial cues that children might have used to locate the targets. Therefore we looked at signed errors, first on the group level, to find out whether different age groups exhibited different response biases. To that end, signed errors on strip trials, for which targets were distributed along one dimension in a clear spatial order, were collapsed across scaling factors. Fig. 3 shows that 3-year-olds, and to a lesser extent 4-year-olds, located the eggs too far to the left (negative errors) for targets on the right side of the strip and too far to the right (positive errors) for targets on the left side of the strip. In other words, responses were biased toward the middle of the strip, and deviations increased the further the target locations were away from the middle. The three oldest age groups showed a different pattern, exhibiting a bias toward the ends of the strip, which was stronger the further the target locations were away from the edges. Adults, for example, were fairly accurate for targets that were 3 cm away from either the left or right edge, but their accuracies were lower for targets that were 9 cm away from the edges. Here again, 5- and 6-year-olds performed more similarly to adults than to the two younger age groups.

2.3. Relative accuracy on individual level

To shed light on individual response patterns, we analyzed whether a participant preserved the relative spatial order of hiding locations. More specifically, we analyzed whether the x-coordinates of the responses reflected the ordinal relation of the 7 hiding locations on the strip trials (Fig. 1a). For example, if a child's responses preserved the order of the true hiding locations, the response for the

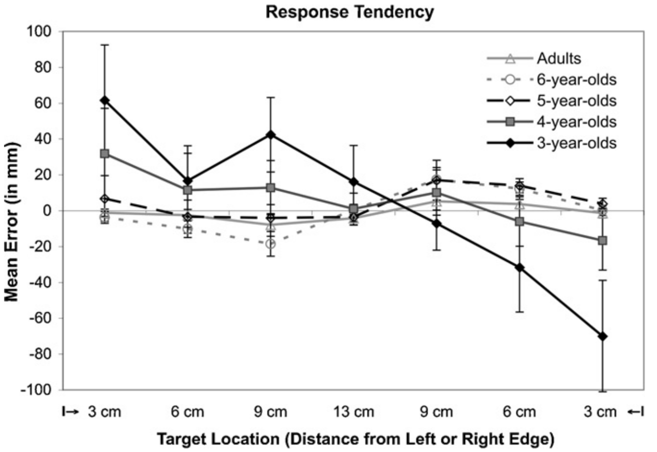

Fig. 3. Response tendencies (signed errors) by age group for the different target locations on the strip. The 13 cm target location was in the middle of the 26 cm long strip. Positive errors stand for a response bias toward the right side of the field. Error bars represent standard errors of the means.

hiding location at 3 cm from the left edge should be to the left of the response for the hiding location at 6 cm from the left edge. Preservation of the relative spatial order of the hiding locations can serve as an index of whether children responded systematically and in a spatially consistent pattern, independent of absolute response accuracies.

First, we calculated how many children in each age group preserved the spatial order of all 7 hiding locations across the different scaling factors (1:1, 1:2, and 1:4), allowing for one error (no more than one adjacent switch). The results are summarized in Table 2 and show a developmental progression, with only four (29%) of the 3-year-olds, about half (55%) of the 4-year-olds, and almost all (95%) 5-year-olds preserving the overall order. Fisher's exact tests confirmed that differences between 3- and 4-year-olds and between 4- and 5-year-olds were significant at $p < .05$ and $p < .01$, respectively. After age 5, there was no significant developmental progression on this measure (Fisher's exact test, all $ps > .5$). Table 2 also shows the numbers for scaled trials separately. Here, the order of only three locations had to be preserved for scaling factor 1:2 and 1:4, respectively, so larger numbers could be expected. However, the side of the hiding locations were alternated across trials (e.g., 9 cm left, 6 cm right, 3 cm left), so direct comparisons with the previous trials were difficult. Table 2 shows that the numbers were almost the same for 1:2 and 1:4 trials (Fisher's exact test, all $ps = 1.0$), and that after age 5, all but one participant preserved the spatial order on scaled trials.

2.4. Left–right reversals

Finally, we analyzed the number and nature of extreme responses in order to examine on which trials and at which ages children especially had problems. Close inspection of relative distances of

Table 2
Number (and percentage) of participants who preserved the relative order of hiding locations in the 'strip' fields per age group, for all (minus one) locations, for 1:2 trials only and for 1:4 trials only.

	N	All (−1) locations *n* (%)	1:2 trials *n* (%)	1:4 trials *n* (%)
3-Year-olds	20	4 (20)	9 (45)	8 (40)
4-Year-olds	20	11 (55)	15 (75)	15 (75)
5-Year-olds	20	19 (95)	19 (95)	20 (100)
6-Year-olds	20	18 (90)	20 (100)	20 (100)
Adults	12	12 (100)	12 (100)	12 (100)

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Table 3
Number of left–right reversals (and number of participants who produced left–right reversals) by age group, scaling factor, and reference features.

	Scaling factor		Reference features			Total
	1:2	1:4	Strip	Rectangle	Circle with landmarks	
3-Year-olds	21 (5)	67 (13)	83 (17)	5 (1)	0	88 (18)
4-Year-olds	15 (7)	20 (5)	29 (8)	4 (3)	2 (1)	35 (12)
5-Year-olds	6 (5)	4 (3)	4 (3)	6 (5)	0	10 (8)
6-Year-olds	1 (1)	1 (1)	0	1 (1)	1 (1)	2 (2)
Adults	0	0	0	0	0	0
Total	43 (18)	92 (22)	116 (28)	16 (10)	3 (2)	135 (40)

individual children's responses showed that there were a few responses of 3- and 4-year-olds that were not only far off target but also on the opposite side of the fields than the hiding locations. These responses might have contributed to the large variance in the younger age groups' absolute distances reported above and deserve a closer look.

All the trials with hiding locations distributed on either side of the strips, rectangles, and circles were analyzed for outliers and extreme values. Responses were identified that had *x*-values of more than 1.5 times the inter-quartile range above the upper quartile or below the lower quartile per trial. With this procedure, 137 out of 1656 responses (8%) were identified as outliers; these were produced by 40 participants. Half of these 40 only produced one or two outliers. Ten participants produced 50% of all the outlier responses; eight of these participants were age 3 and two age 4. With two exceptions, all outliers were located toward the opposite side of the fields than the hiding locations. Table 3 shows the number of left–right reversals (i.e., outliers toward the opposite side) and the number of participants who produced at least one outlier by age group. The table shows decreasing numbers of reversals with increasing age. Children younger than age 5 made almost all the reversals on strip trials. The 3-year-olds produced more reversals on 1:4 trials than 1:2 trials, and this distribution was significantly different from the 4-year-olds', $\chi^2 = 4.36$, $p < .05$.

We further examined the possibility that these extreme deviations were due to grouping strategies. That is, young children might have confined their responses to a small area of the field, placing the peg in roughly the same spot for all trials regardless of the actual position of the target. Such a response pattern could account for the very large deviations on some of the trials. Hence, the response distributions of the 20 participants who produced more than two outliers were inspected. Three 3-year-olds and two 4-year-olds responded within a maximum range of 10 cm in diameter for at least one of the fields. Three 3-year-olds confined their responses to a range of 6 cm on one of the fields. These response groupings occurred about equally often on strips, rectangles, and circles. None of the participants showed a grouping pattern consistently for all three fields, and only two 3-year-olds showed a grouping pattern on two fields.

3. Discussion

The present results suggested that accuracy in spatial scaling, in terms of absolute errors as well as preservation of the relative order of hiding locations, undergoes considerable development, most marked between 3 and 5 years of age. Thus, children showed earlier competence than in some previous studies (Liben & Downs, 1993; Liben & Yekel, 1996; Uttal, 1996), likely due to the fact that a number of complexity factors were eliminated in the present study that seem to contribute to children's difficulties in map-reading tasks. These include the need to memorize the maps and to perform a number of additional spatial transformations aside from scaling, such as mental rotation, perspective taking, and changes in dimensionality. However, the present results are in line with previous studies using very simple scaling tasks (Huttenlocher et al., 1999, 2008; Vasilyeva & Huttenlocher, 2004), which suggested a basic understanding of scaling at age 3, with major improvements between 3 and 5 years of age. Also consistent with these previous studies, we found no overall gender difference in accuracy.

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Although all age groups performed best on the trials with circular boundaries and landmarks, this was particularly true for the youngest two age groups. These results are in line with previous findings (Shusterman et al., 2008) showing that the presence of landmarks facilitated preschoolers' performance in an object placement task. Landmarks might have provided unambiguous reference points that helped to establish representational (symbolic) correspondences and promoted the use of associative strategies based on proximity. In contrast, for strips and rectangles only the boundary lines could be used for reference, which all looked very similar and only differed in spatial orientation. Young children might have had difficulties choosing an optimal reference – a notion that is also consistent with the results for strips and rectangles.

The 3-year-olds on average produced the largest errors on the strips, whereas all other age groups made the largest errors on the two-dimensional rectangles. This result was unexpected, considering that there was less room for error on strip trials and that previous investigations suggested that 3-year-olds would perform better when targets were distributed along one dimension than when they varied along two dimensions. In-depth analyses of outliers and extreme values revealed that these errors were produced predominantly on the strips by 3-year-olds and to a lesser extent by 4-year-olds. They were almost exclusively located on the opposite side of the strips, as if the children had chosen the wrong edge of the strip as a reference point. In agreement with this analysis, Huttenlocher, Newcombe, and Sandberg (1994) showed that a sizeable number of 4-year-olds made similar right/left reversal errors on a spatial memory task that did not require scaling. Grouping strategies could not fully account for these extreme responses. Only 8 of the 20 participants with more than two outliers grouped their responses within a range of 10 cm in diameter – a fairly lenient criterion given that, at their largest extensions, the circles and rectangles were only 20 cm and 22 cm wide, respectively. Moreover, grouping patterns were not found more often for strip trials than for the other two fields. Thus, it is more likely that children generated a mental mirror image of the space rather than representing it in the same spatial orientation.

Analyses of signed errors indicated that other response biases were also at work. Whereas 3- and 4-year-olds tended to shift their responses toward the middle of the strips, 5- and 6-year-olds tended to shift them toward the ends of the strips. These response tendencies were stronger when the target locations were further away from the middle for the younger children and from the ends for the older children. Thus, the 5- and 6-year-olds performed more similarly to adults, exhibiting the same response tendency toward the ends, as opposed to the younger two age groups, who showed a central tendency. Similarly, Huttenlocher et al. (1994) reported that when looking for a toy buried in a long, narrow sandbox, young children's responses were systematically biased toward the center of the sandbox. They interpreted this response pattern as evidence that young children treated a bounded homogeneous space as a single category with a prototypical location at its center. Starting around 4–5 years, children showed signs of mentally subdividing a two-dimensional space. In line with these results, our findings suggest that the younger children in our study may have processed the hiding space as a whole, locating the target within this homogenous entirety and thereby gravitating toward the middle of the area. Starting around age 5, children might have taken a more analytical approach, trying to relate the target locations to a landmark or – for lack of landmarks – to the closest edge of the field, thereby shifting toward those reference features. This interpretation is consistent with the traditional view that objects are perceived as undifferentiated wholes early in development (under the age of about 5 years; Inhelder & Piaget, 1959), whereas later they are perceived as a conjunction of attributes, features, or dimensions (Smith, 1989).

Analyses of accuracies at different scaling factors provided further insight into cognitive strategies. Participants of all ages performed better on trials that did not require scaling than on those that did, and this difference decreased with age. However, there were no significant differences between scaling factors 1:2 and 1:4. This suggested that children did not simply reproduce absolute distances (e.g., 1.5 cm from the tree) or encode absolute distances and transform them by a scaling factor. If this were the case, larger errors could have been expected for larger scaling factors, and slight uncertainties would have increased as a function of scaling factor. Rather, children encoded relative distances (e.g., the object is at 1/4 the distance from the tree to the house) and solved the task by reproducing ratios. This type of relative coding preserves the relation between distances even if applied in a different size space, as opposed to absolute distances that need to be transformed.

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This interpretation is in line with a model proposed by Huttenlocher et al. (1999), suggesting that toddlers code locations in enclosed spaces by relating visible distances to one another rather than imposing units of measures. It is important to note that this view does not imply that children are able to perform proportional computations or have an abstract understanding of ratios at this age. Children most likely use an intuitive or holistic strategy, reproducing *perceptual* ratios, rather than performing abstract computations. For example, children might have used a strategy to mentally stretch or shrink a layout in a way that preserves metric relations, similar to imagining a magnifying glass that expands all dimensions simultaneously (Vasilyeva & Huttenlocher, 2004). This may explain why children can perform basic spatial scaling transformations at an age when they are still unable to solve proportional reasoning problems presented in more abstract formats (Boyer, Levine, & Huttenlocher, 2008; Brainerd, 1981; Chapman, 1975; Falk & Wilkening, 1998; Inhelder & Piaget, 1958; Piaget & Inhelder, 1951/1975).

Whereas in our study accuracy was not affected by the magnitude of scaling transformations, previous results (Vasilyeva & Huttenlocher, 2004) showed a decrease in accuracy for larger transformations. A number of methodological differences could account for these contrasting findings. First, Vasilyeva and Huttenlocher manipulated scaling factor by varying the size of the referent space. Localization of an object in a larger room may be more difficult just because there is greater uncertainty and more room for error. In the present study, scaling factors were manipulated between maps rather than between referent spaces (fields), in order to guarantee a constant level of error variance in responses and in precision of measurement across different scaling factors. A further difference was that in our task the referent spaces were smaller than those used by Vasilyeva and Huttenlocher, who used two referent spaces of 76 cm by 107 cm and 244 cm by 341 cm. Presumably, increasing uncertainty with increasing referent space sizes in previous studies could have been due to children losing the overview over the referent spaces. In our study, the viewing angle was held constant and therefore could not have been a confounding factor. Furthermore, an overview of both the map and the reference space could have facilitated the visual comparison and thus might have promoted the use of a perceptual strategy of coding and comparing relative distances. Whereas a small-scale presentation like ours allows for parallel processing of all relevant spatial features, large-scale presentations require children to move their eyes, perhaps even their bodies, and thus require serial encoding of spatial properties. Serial encoding and comparison necessarily involves memory; hence different strategies may be favorable in large-scale and small-scale spaces. Future studies should address whether the same results would be obtained in large-scale spaces that exceed the visual field, if the size of the referent space is kept constant.

Finally, it is worth noting that some 3-year-olds produced large errors even on un-scaled trials. This suggests that they not only had difficulties with spatial scaling, but also with mapping spatial information from one space to another. Thus, a limiting factor on young children's performance in object location tasks (and possibly also map-reading tasks) may be the ability to encode the relation of the target object to reference features, or to maintain and use this relational information. In order to use relational information in a mapping task, one needs to compare relational information in one space to relational information in the other space, which requires an understanding of relations between relations. Our results suggest that young children either applied a holistic approach, which side-steps the problem, or if they tried to use a relational strategy, they often failed, especially if the only available reference features were boundary lines. These findings are in line with the *relational shift* hypothesis (Gentner & Rattermann, 1991; Uttal, Gentner, Liu, & Lewis, 2008), which postulates increasing sophistication of relational thought.

To summarize, the present results showed that spatial scaling abilities undergo considerable development in preschool years, with significant improvement between 3 and 5 years of age. Signed errors further suggested a developmental progression from treating the referent space as a homogenous entirety toward a more fine-grained and more adult-like response pattern. Thus, the findings confirm the developmental sequence deduced from the results of a variety of previous studies. Importantly, the present study also revealed large individual variance in spatial scaling skills at a young age when considerable development appears to take effect. Future research may show how such individual differences in spatial scaling skills relate to performance on more complex tasks that build upon those skills. Specifically, some open questions are how relational thinking in the spatial domain affects children's later understanding of mathematical concepts such as fractions, or proportional reasoning in general. Investigating these questions may allow us to gain a better understanding of how to identify children at risk of developmental delays at very young ages, and exactly what type of risk these delays pose in terms of later cognitive functioning.

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