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Fitting objects into holes: On the development of spatial cognition skills

Helena Örnkloo[1] and Claes von Hofsten[1]

Department of Psychology, Uppsala University

[1] Address for correspondence: Department of Psychology, Uppsala University, Box 1225, S-75142 Uppsala, Sweden. Fax number: 018-4712123. Email Addresses: Helena.Ornkloo@psyk.uu.se, Claes.von_hofsten@psyk.uu.se

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Abstract

14- to 26-month-old infants' understanding of the spatial relationships between objects and apertures was studied in an object manipulation task. The task was to insert objects with various cross-sections (circular, square, rectangular, elliptic, and triangular) into fitting apertures. A successful solution requires the infant to mentally rotate the object to be fitted into the aperture and use that information to plan the action. On half the trials the object was presented standing up and on the other half it was lying down. The results showed that infants solved the problem consistently from 22 months and that a successful solution was associated with appropriate pre-adjustments before the hand arrived with the block to the aperture. No sex differences were found.

During the second year of life, infants are fascinated by problems of how to relate objects to each other. For instance, they find it very attractive to pile objects, put lids on pans, and insert objects into holes. The ability to solve such problems reflects infants' developing spatial perception and cognition. To fit an object into an aperture, for instance, infants must understand how the 2-dimensional aperture is related to the 3-dimensional object form. Finding this relationship requires the subject to see or imagine different projections of the object. Planning the fitting action in a prospective and economical way also requires the subject to imagine how to rotate the object in order to make it fit. These are rather sophisticated expressions of spatial cognition. They include mental rotation, as well as, the ability to imagine goal states and understand means-end relationships. Thus, fitting tasks provide a window for learning about the development of these spatial abilities and how children go about solving them. Toy manufacturers have for a long time exploited infants' interests in fitting tasks and such tasks have sometimes been included in intelligence tests for young children (Bayley, 1969), but there are almost no systematic experimental investigations of the cognitive abilities that underlie this development. The purpose of the present study was to provide such data for 1- to 2-year-old infants. Because there are so few earlier studies on this problem, the aim was by necessity explorative. The questions asked were related to the motor competences as well as to the perceptual and cognitive capabilities of the children. What are the major transitions in the acquisition of these skills? What are the strategies used at different ages? To what degree are the strategies predictive and to what degree do they rely on feedback?

Goal-directed actions are guided by perceptual and cognitive processes and involve planning and anticipation (see e.g. Hommel, et al. 2001; von Hofsten, 2004; Umilta, et al. 2001). Thus, by studying actions in young children we can get insights into how they plan their actions and what information they use for that purpose. For instance, when infants reach for objects at 5 to 6 months of age, the hand opens up before or during the approach (von Hofsten

& Rönnqvist, 1988), is rotated to align itself with the longitudinal axis of the object before it is encountered (Lockman, Ashmead & Bushnell, 1984; McCarty, Clifton, Ashmead & Goubet, 2001; von Hofsten & Fazel-Zandy, 1984), showing that infants at that age perceive object properties relevant for grasping. If the object is moving (von Hofsten, 1980; 1983), infants reach for a point in space where the hand and the object will meet and not where the object is seen at the initiation of the reach showing that they accurately perceive object velocity and anticipate future locations of the object. The fitting task is more demanding than a simple grasping task, however, in the sense that one object is used as an instrument for acting on another one (Achard & von Hofsten, 2002). This requires the ability to perceive, not only the simple geometric properties of objects, but also their affordances, that is, what they can be used for and how. The object used as an instrument serves as an extension of the limbs (Connolly & Dalgleish, 1989) and is the means to accomplish a more distant goal. To master such actions require elaborate planning. Toward the end of the first year, infants begin to show such understanding (Case-Smith, 1995). The manipulation of the object depends on the particular purpose of the action (Manoel & Connolly, 1998). Claxton, Keen, & McCarty (2003) found that 10-month-old infants picked up a ball in one way if it is going to be fit into a tube and in another way if it is going to be thrown into a tub.

McKenzie, Slater, Tremellen, & McAlpin (1993) challenged 10-month-old infants to reach for a rod that could only be accessed through a vertical or horizontal aperture. The rod was either positioned aligned with, oblique or perpendicular to the aperture. The infants perceived the relationship between the rod and the aperture more easily when they were aligned than when they were perpendicular to each other. McCarty, Clifton, & Collard (1999) studied how 9-, 14-, and 19-month-old infants picked up a spoon with food, the handle of which was either oriented left or right. If the spoon was picked up with the right hand and its handle was oriented to the left, a more complicated procedure was required to get the spoon appropriately oriented to deliver the food to the mouth. McCarty et al. (1999) found that in such cases, the 9-month-olds used a feedback strategy and the handle was only reoriented after the food had reached the mouth. The 14-month-olds used a “partially planned strategy” and the spoon was reoriented only after it had been picked up but before it reached the mouth. Finally, the 19-month-olds picked up the spoon in a way that was fully adjusted to the task.

Meyer (1940) studied how 18-month- to 5½-year-old children went about trying to solve various spatial tasks. Among other things she challenged infants to insert a rectangular object into a rectangular hole and to insert arrangements with two objects connected with a long rod into a square hole. Meyer (op. cit.) classified children’s behaviors in three stages. In the youngest children (18–24 months of age) she found no justments of object orientation before they attempted to insert them into the hole. The 2-and-3-year-old children were able to make some pre-adjustments, but could not always repeat a successful trial. Finally, by 3 years of age, the children understood that they had to adjust the block in certain ways before inserting it into the hole. It was noted whether the child was successful or not.

In contrast to these results, Gesell & Thompson’s (1934), and Bayley’s (1969) age criteria for various fitting tasks are much lower. They state that infants will fit a ball into a circular aperture at 12 1/2 months and a cube into a square aperture at 19 1/2 months. Geerts, Einspiler, Dibiasi, Garzarolli, & Bos (2003) video-recorded how 14-, 18- and 25-month-old infants went about inserting a cube into a square aperture. They found that the majority of the 14-month-olds managed to do that. However, neither Gesell & Thompson (1934), Bayley (1969), nor Geerts et al. (2003) reported whether the infants made pre-adjustments of the hand in order to facilitate the insertion of the object into the aperture.

The task of passing an object through an aperture into which it snugly fits, requires the solution of at least three spatial problems. First, the subject has to understand that in order to insert the object into the aperture they had to place it over the aperture. Secondly, the longitudinal axis of the object has to be oriented perpendicular to the aperture in order to insert it. Thirdly, the object has to be oriented in such a way as to make its cross-section correspond to the orientation of the aperture. Passing a ball through an aperture constitutes the easiest possible fitting task because it fits in any orientation. A cylinder presented standing up is also expected to be relatively easy because the only additional requirement is to maintain the vertical orientation of the cylinder when transporting and placing it over the aperture. In order to insert a cylinder presented lying down; it must be raised up before placed over the aperture. For every other fitting task, all of the three problems have to be solved. The difficulty of the third problem is a function of how specific the orientation has to be. Thus, an object with a square cross-section is easier to fit into a fitting aperture than a rectangular or triangular form because it fits in more ways.

A pilot study

In order to explore how young children approach the object-aperture problem at different ages, Achard & von Hofsten (2000) presented blocks and apertures to 71 12-, 16-, 20-, and 24-month-old children. The objects included a ball (3.8 cm in diameter) and a cylinder (3.6 cm in diameter and 3.1 cm long) that were to be fitted in to a circular aperture (4.0 cm in diameter), a cube (2.9 cm side) and an elongated block (5.8 cm long) with a square cross section (2.9 cm side) that were to be fitted into a square aperture (3.0 cm side), and a block with an equilateral triangular cross section (4.1 cm side, and 3.9 cm long) that had to be fitted into a triangular aperture (4.7 cm side). They were either oriented with the fitting surface parallel to the aperture or perpendicularly to it. The objects could only be fitted into the apertures in specific ways except for the ball that fitted the round aperture in whatever orientation it was presented in. This object was always presented first. If the infant did not insert it into the aperture even after several demonstrations and encouragements to insert it, the experiment was discontinued. Only 12 out of the 22 12-month-olds but all the older infants solved this task and could thus be included in the remaining part of the experiment. A majority of the 12-month-olds that passed the ball task also inserted the cylinder into the circular aperture, but was unsuccessful with all the other object forms (see Table 1). The 16-month-olds inserted the cylinder on almost every trial, the cube on 2/3 of the trials, but the other objects much less frequent. A dramatic shift in the ability to solve the task occurred between 16 and 20 months of age, as can be seen from Table 1. While the 16-month-olds inserted the triangular block in just 1 trial out of 5, the 20-month-olds did it in almost 2 trials out of 3.

------------------------ Insert Table 1 about here ---------------------------

Pre-adjustment was defined as a reorientation of the object in a way that facilitated its insertion into the aperture. Infants' tendency to pre-adjust object orientation before arriving at the aperture box was reflected in their tendency to rise up the objects presented with the fitting surface perpendicular to the horizontal aperture so that it became parallel to it. The 12-month-olds had no such systematic tendency. The 16-month-olds raised up the cylinder during the approach but not the other blocks. From 20 months, the block with the square cross section was raised up in a majority of the trials while the block with the triangular cross section was not even systematically raised up at 24 months. The lack of such a tendency could have been a function of the fact that the triangular block was shorter than the width of its cross section. In addition to making the longitudinal dimension less distinct, the slanting longitudinal sides made it difficult to grasp the object across them. Therefore, most infants grasped this block across the fitting cross-sections which occluded them from view and made it awkward to reorient the cross sections in such a way as to fit them into the aperture.

The results suggest that an understanding of the object aperture problem develops during the second year of life. While only about half the 1-year-olds understood the idea of inserting a ball through an aperture, the 2-year-olds inserted successfully blocks that had to be oriented in specific ways to get through the aperture. These data fit Bayley's (1969) norms rather well.

Except for the 1-year-olds, the task proved to be very motivating. The 16-, 20-, and 24-month-olds completed, on the average 15 of the 16 trials included in the experiment.

The present study

The experiment by Achard and von Hofsten (2000) raised several questions. First, as the size, length, and width of the objects varied unsystematically, in addition to how loosely they fitted the aperture, it is not possible to conclude what stimulus variables determined infants' success at different ages. Thus, the found difference between objects in solving the aperture problem could have been a function of their size, form, or the fact that the relationship between length of the blocks and size of the fitting cross sections were different. Furthermore, it is not possible to determine whether the aperture problem was solved by pre-adjustments of object orientation or by trial-and-error. Only the tendency to rise up the objects that were presented lying down was analyzed, but this analysis was also obscured by the fact that the objects varied unsystematically in their length, width, and size.

In order to disentangle the different spatial variables, all objects in the current study were of equal length with the longitudinal axis distinctly larger than the cross-sections. Their dimensions were all 1 mm smaller than the apertures. Seven different cross-sections were used whose circumference was approximately the same but varied with respect to the number of ways they fit into a corresponding aperture. One of the objects was a cylinder and as long as its longitudinal axis was vertical, it fitted in every possible orientation. One object had a square cross-section and it fitted in 4 ways in each of the two vertical orientations. One block had a cross-section in the form of an equilateral triangle and it fitted the aperture in 3 ways in each of the two vertical orientations. One block had a rectangular and one an ellipsoid-like cross-section. They fitted the corresponding apertures in 2 ways in each of the two vertical orientations. Finally there was one object with a cross-section in the form of an isosceles triangle and one in the form of a triangle with unequal sides. The former one fitted one way in each of the two vertical orientations and the other in one way but in only one of the two vertical orientations. All the objects were both presented standing up and lying down.

The object with the triangular cross-section with unequal sides was expected to be the most difficult one. When it was lying down, the subjects had to figure out not only that it should be turned up but also how. If this object was turned up in the wrong way, it would not fit the aperture at all. How the subjects solved the different problems in the fitting task was pursued by examination of the pre-adjustments performed while moving the objects to the aperture, the action outcome, and the time it took to carry out the task. If infants solved the fitting problem by pre-adjustments, then they should, before or during the approach, systematically rise up the objects that were presented lying down and turn all objects in such a way that the fitting cross section is approximately aligned with the aperture. If they solve the problem by trial-and-error there would be no such tendencies. Furthermore, if infants solve the aperture problem by trial and error, the number of correct solutions should increase linearly with time trying.

The choice of hand in solving the task was also examined. According to Fagard & Marks (2000) the laterality expressed depends on the constraints of the task. When it is a new or a complex task, children tend to use their preferred hand more often than in an easy task. Fagard (1998) and Fagard & Lockman (in press) also found that when grasping involved bimanual manipulation, handedness was more distinct than for simple grasping. Thus, it was hypothesized that the choice of hand would be more distinct at the age when the children began to solve the fitting task.

Finally, the relationship between the sex of the subjects and performance was examined. Adult males have earlier been found to have an advantage over females on tasks requiring mental rotation, that is, tasks requiring mental reorientation of a 2D or 3D object (Voyer, 1995). This advantage is, however, much less distinct in children, if at all present (Voyer, 1995;

Roberts & Bell, 2002). Grimshaw, Sitarenios, & Finegan (1995) found a weak relationship between 7-year-old children's mental rotation ability and prenatal testosterone levels. The girls who had a higher prenatal testosterone level performed the mental rotation task faster but not more correctly than the girls who had lower levels. No other effects were significant. According to Grimshaw, Sitarenios, & Finegan (1995) this could indicate that some sex differences on spatial tasks might have a hormonally triggered genetic base.

Four age groups were investigated: 14-month-olds, 18-month-olds, 22-month-olds, and 26-month-olds. The original intention was to include a group of 12-month-olds, as well. Six infants of this age were tested but they had difficulty with understanding the task and none of them was able to insert any of the objects into the aperture. This result is in line with the results from the pilot study. The decision was therefore made not to include this age group in the present study.

Method

Subjects

Altogether 69 healthy infants from 4 different age groups were studied. The youngest group consisted of 8 boys and 8 girls with a mean age of 14.0 months (Sd =3.4 days). The second youngest group consisted of 8 boys and 9 girls with a mean age of 18.0 months (Sd =8.2 days). The second oldest group consisted of 9 boys and 8 girls with a mean age of 22.0 months (Sd =3.6 days). The oldest group consisted of 11 boys and 8 girls with a mean age of 26.1 months (Sd =5.2 days). All infants were born within 3 weeks of the expected date, except 3 girls who were born prematurely. One 18-month-old and one 22-month-old were born 6 weeks early, and one 26-month-old was born 5 weeks early. The preterm children's results are included in the statistics as they did not differ from the rest of their age groups.

Experimental set-up

A set of objects and a box with interchangeable square lids were used for the experiment. Each of the lids had an aperture that corresponded to the cross-section of one of objects. The objects and the box were presented on a table (59.5 x 120 cm) between the experimenter and the subject. The box (14 x 14 x 11.5 cm) was fixed to the table 5 cm from the edge on the side where the subject was seated. The objects were presented on a platform behind the box but at the same level as the box. Two video cameras monitored the experiment. They were placed above and to the sides of the table. The two cameras were fed via mixer (Videonics) into a video-recorder (JVC) (see Figure 1).

-------------------- Insert Figure 1 about here -------------------

Stimuli

Different lids could be applied to the box. Each lid had an aperture with one of the following seven shapes: circular (3.5 cm diameter), square (3.2 cm side), rectangular (2.5 x 4 cm), ellipse-like (a central part of this object had a cross-section of 1.4 x 2.8 cm and was surrounded by two half cylinders with a diameter of 2.8 cm), equilateral triangular (4 cm sides), isosceles triangular (4 x 4 x 2.5 cm sides) and right-angled triangular with unequal sides (4 x 4.5 x 2.5 cm sides). The cross-sections of all blocks had approximately the same circumference. It varied between 10.5 cm and 13 cm. There was one specific aperture for each block. The objects were 1 mm smaller than the apertures in all dimensions and measured 7 cm in length. There were 4 differently colored copies of each object (red, blue, yellow, and green). The combination of colored objects was randomly determined for each experiment (see Figure 2).

-------------------- Insert Figure 2 about here -------------------

Procedure

After having greeted the child and the parent, the experimenter explained the purpose of the study and the parent signed an informed consent form. Meanwhile, the experimenter played with the child to become familiar with him or her. The parent was then invited to sit in the chair with the child in his/her lap. He/She was permitted to encourage the child, but not to give any assistance in the trials. The experimenter sat opposite to the child and presented the objects one by one. The objects that were not used on a particular trial were out of reach of the child. Before the experiment started, the child was introduced to the box and the experimenter demonstrated how objects could be inserted into the box through the aperture. The demonstration objects, two rubber balls and a steel rod, were much smaller than the experimental objects and required no special adjustments to fit the aperture. After the demonstration, they were handed to the child so that he/she could manipulate them for a while. The experiment begun after the child had inserted one of these objects into the aperture.

The experiment consisted of 28 trials organized into two blocks. In each block, the 7 objects were presented in a vertical as well as a horizontal position. The order between the stimuli in each block was randomized. When the objects were presented standing up, the orientation of the object's cross-section was always identical to the orientation of the aperture. When they were presented lying down, the longitudinal axis was oriented radially from the subject, and the shortest axis of the cross-section was the horizontal one. The exception to this rule was the ellipse-like object that could only be presented with the longest axis of the cross-section oriented horizontally.

The objects were presented on the platform at the far side of the box. The child was encouraged to pick up the object and insert it into the aperture. The lids and the objects were changed between trials. Sometimes, when the child was unable to insert the object into the box, the experimenter did it in his/her place, but was careful to do it with the other hand covering the view of how it was done. Immediately after this, an object with the same shape but another color was given to the child for a new attempt. However, the second trial was not included in the analysis; it was only there to avoid boredom, and challenge the child to continue.

The duration of the whole experiment was very variable, but most of the children, finished their session in 30 minutes. If the child was very attentive and eager to perform, it could be completed in as little as 20 minutes. If the child was easily distracted and un-concentrated it could take as long as 1 hour including pauses. The whole experiment was video-recorded. Before analyzing the records, the videotapes were time-coded with a digital clock giving the time in 1/100 s.

Data analysis

The actions on the objects were analyzed in the following way:

Laterality: Each trial was coded in terms of whether the object was grasped with the right, left, or both hands, and whether the object was passed between the hands during the attempts to insert it into the aperture. A laterality score defined as the proportion of trials where the infant used the right hand was then calculated. In doing so, bimanual reaches were counted as half a trial.

Appropriate pre-adjustments of object position: It was judged whether the operations on the object before it touched the lid of the aperture-box were appropriate pre-adjustments for inserting it into the slot. The judgment was made at the time the object touched the lid of the aperture box and was always yes/no. Each trial was judged in two ways with respect to how the object was placed over the aperture (see Figure 3). Was its longitudinal axis vertical and was its cross-section aligned with the aperture? The orientation was considered vertical if the longitudinal axis deviate less than 30º from verticality. This cutoff was arbitrarily chosen. The horizontal alignment was only meaningful to judge if the vertical orientation was appropriate. The cross-section was judged to be appropriately oriented if it deviated less than 30º from the orientation of the aperture (see Figure 3). This cutoff was also arbitrarily chosen. If both the vertical and horizontal pre-adjustments were appropriate, the object ended up in a position approximately correct for inserting the object into the box. The horizontal and vertical pre-adjustments were separately coded. Thus, if the child failed to place the object vertically on the aperture the error was coded as a vertical error. If the object was placed vertically on the aperture but it wasn't adjusted appropriately to fit the aperture it was coded as a horizontal error. The percentage of appropriate vertical pre-adjustments was calculated from the completed trials with horizontally presented blocks. The percentage of appropriate horizontal pre-adjustments was calculated from the completed trials with vertically presented blocks plus the trials where the horizontally presented blocks had been raised up. The coding of pre-adjustments was not dependent on success or failure. It was made at the time of touch when it was not yet known whether the attempt was going to result in a successful insertion or not.

Action outcome: For each trial, the attempts to insert the object into the aperture were coded as successful or unsuccessful.

Time: The time from the grasping of the object until it touched the lid of the aperture box was registered from the video recordings, and from that time until it was either inserted into the aperture or the subject gave up.

Reliability: The vertical and horizontal pre-adjustments were judged by a second coder. Cohen's Kappa was used to evaluate the inter-rater reliability. The two coders disagreed on 31 out of 302 on the cases. Only the results of the primary coder were used in the analysis of the results. Cohen's Kappa was satisfactory both for the horizontal pre-adjustments (r = 0.87), and for the vertical ones (r = 0.80).

Results

Number of completed trials

The task of inserting objects into apertures proved to be very attractive and the subjects completed 1 677 trials out of 1 932 possible. If the subject grasped the object presented and placed it on the aperture, the trial was considered completed. The 14-month-olds completed 69% of the trials, the 18-month-olds 86%, the 22-month-olds 93%, and the 26-month-olds 97%.

Laterality

The laterality score (proportion right handed reaches) was calculated for each subject. Figure 4 shows the distribution of laterality scores for each age level of the study. Figure 4 shows that the children used the same hand in a large majority of the trials indicating that the task was challenging. The overall proportion of reaches made with the right hand was 80%. Eight out of the 69 children (11%) used the left hand more often than the right, but none of the children used the left hand exclusively. 9 children used the right hand on all trials exclusively, and 4 additional children used the right or both hands. Bilateral reaches or reaches where the block was swapped between the hands were relatively rare. They were most common at 14 months, when they constituted 10% of the reaches. A nonparametric Wilcoxon test showed that the right hand was used significantly more often than the left at all ages: 14 months: $z = -2.512$; $p = 0.012$, 18 months: $z = -2.743$; $p = 0.006$, 22 months: $z = -2.819$; $p = 0.005$, and 26 months: $z = -2.918$; $p = 0.004$.

-------------- Insert Figure 4 about here ----------------

Successful insertions in aperture

14-months-old succeeded in inserting the object in 20% of the trials, 18-months-old succeeded in 33%, 22-months-old in 78%, and 26-months-old in 81% of the trials. Figure 5a shows the average percentage of successful insertions (successes/(successes + failures)) into the box for the standing objects and Figure 5b the average percentage of successful insertions for the objects lying down.

------------- Insert Figure 5a and 5b about here ----------------

A split-plot factorial ANOVA was used to test the results with Object form (7) and Presentation mode (2) as within subject variables and Age (4) and Sex of the subject (2) as between subject variables. It showed a main effect of Object form ($F(6, 378) = 75.499$; $p < 0.001$, $\eta^2 = 0.545$) (see Figures 5a and 5b). The more ways an object fit into the corresponding aperture, the more successful the infants were. Thus, the infants were most successful with the cylinder and least successful with the triangular object having a cross-section with unequal sides. The Bonferroni adjusted pairwise comparisons (5% level) for the different objects showed that the only non-significant contrasts were those between rectangle and ellipse, square and equilateral triangle, and isosceles triangle and unequal-side-triangle.

There was a main effect of Presentation mode (standing-lying) ($F(1, 63) = 28.644$; $p < 0.001$, $\eta^2 = 0.313$). The infants were more successful with the objects standing up than with those lying down. This was expected because the standing objects were presented with the cross-section aligned with the aperture. There was furthermore a significant interaction between the Presentation mode and Object form ($F(6, 378) = 3.828$; $p = 0.001$, $\eta^2 = 0.057$). This means that the increase in difficulty when presenting the objects lying down was different for the different objects. This can be seen in Figures 5a and 5b. The difference in success between the vertical and horizontal cylinder was less than the difference between presentation modes for any of the other objects.

There was a significant main effect of Age ($F(3, 63) = 58.361$; $p < 0.001$, $\eta^2 = 0.735$). The older the children, the more successful they were. The Bonferroni adjusted pairwise comparisons showed significant differences ($p < 0.05$) between the two younger groups (14 and 18 months) and the two older groups (22 and 26 months). No significant difference was found within those groups. An interaction between Age and Object form was obtained ($F(18, 378) = 5.662$; $p < 0.001$, $\eta^2 = 0.212$). The superiority of the actions on the cylinder was much greater for the younger than for the older infants and the inferiority of the actions on the objects with the more difficult triangular cross-sections was greater for the older than the younger infants. There was no interaction between Age and Presentation mode ($F < 1.0$).

Finally, the boys and the girls performed the task equally well. There was no main effect of sex on success rate ($F(1, 59) = 0.402$; $p = 0.5$) and there was no interaction between sex and the age of the children ($F(3, 59) = 1.764$; $p = 0.16$).

Pre-adjustments

Table 1 shows the percentage of appropriate pre-adjustments (both vertical and horizontal) before the object touched the lid of the box for each object at each age. A split-plot factorial ANOVA was used to test the results with Object cross-section (7) and Standing-lying Presentation mode (2) as repeated measurement variables and Age (4) and Sex of the subject (2) as between subject variable. Significant main effects were obtained for Object form ($F(6, 378) = 80.936$; $p < 0.001$, $\eta^2 = 0.562$), Presentation mode ($F(1, 63) = 98.567$; $p < 0.001$, $\eta^2 = 0.610$), and Age ($F(3, 63) = 109.072$; $p < 0.001$, $\eta^2 = 0.839$). Significant interactions were found for Object form x Age ($F(18, 378) = 4.346$; $p < 0.001$, $\eta^2 = 0.171$), Presentation mode x Age ($F(3, 63) = 4.345$; $p = 0.008$, $\eta^2 = 0.171$), and Object form x Presentation mode ($F(6, 378) = 4.415$; $p < 0.001$, $\eta^2 = 0.065$). Finally, there was no main effect of sex on rate of appropriate pre-adjustments ($F(1, 59) = 1.814$; $p = 0.18$) and no interaction between sex and the age of the children ($F(3, 59) = 0.194$; $p = 0.9$).

------------- Insert Table 1 about here ----------------

The subjects' tendency to orient the longitudinal axis of the object vertically and their tendency to make its cross-section fit the aperture were independently evaluated. Both show clear developmental trends.

Vertical pre-adjustments: The tendency to pre-adjust the objects and place them over the aperture in a vertical position can be seen in Figure 6. As the objects all had the same length, the cross-sections of them should be irrelevant for making this kind of pre-adjustment. As can be seen from Figure 6 this was not quite the case. The youngest infants had a greater tendency to rise up the horizontally placed cylinder than the objects with triangular cross-sections. The infants rarely turned down the objects presented standing up. It almost only happened for the youngest infants (around 25%) and then mostly after they had failed to insert them into the aperture. There were no main difference between boys and girls ($F(1, 126) = 0.926$; $p = 0.3$) and there was no interaction between sex and the age of the children ($F(3, 129) = 1.126$; $p = 0.3$).

A split-plot factorial ANOVA with Object form (7) as repeated measurement variable and Age (4) as the between subject variable was used to test the tendency to turn up the lying down objects into a vertical position. Main effects were found both for Object form ($F(6, 378) = 12.278$; $p < 0.001$, $\eta^2 = 0.163$) and Age ($F(3, 63) = 13.898$; $p < 0.001$, $\eta^2 = 0.398$) and there was an interaction between Object form and Age ($F(18, 378) = 1.724$; $p < 0.05$, $\eta^2 = 0.076$). Bonferroni adjusted pair-wise comparisons between consecutive age-levels show a significant improvement in performance between 18- and 22-month-olds. Almost all 22-month-old infants raised up the cylinder as can be seen from Figure 6.

It can be seen from Figure 6 that the 18-month-olds had a much smaller tendency to turn up the asymmetrical blocks that were presented with the largest side of the cross-section oriented vertically than the other blocks. This difference was statistically significant ($t(16) = 5.731$; $p < 0.000$). The object with the ellipse-like cross-section looked very much alike the one with rectangular cross-section. The main difference was that the object with the ellipse-like cross-section could not be presented with the largest cross-section oriented vertically. It was raised up significantly more often than the object with the rectangular cross-section ($F(1, 16) = 14.222$; $p = 0.002$, $\eta^2 = 0.471$). .

------------- Insert Figure 6 about here ----------------

The appropriate pre-adjustments were either followed by successful or unsuccessful insertions. Figure 7 illustrates the tendency to succeed or fail to insert the object into the aperture after an appropriate pre-adjustment. Figure 7 shows that for the 14- and 18-month-olds, appropriate pre-adjustments were as likely to result in successes as failures to insert the object. In contrast, when the 22- and 26-month-olds made appropriate pre-adjustments, they succeeded most of the time. Figure 7 also shows that when infants failed to adjust the orientation of the object ahead of time, they almost never succeeded in inserting the object into the aperture.

--------------- Insert Figure 7 about here ----------------

Horizontal pre-adjustments: The horizontal orientation was considered appropriate if the deviation was less than 30º from the orientation of the aperture. Because the objects fitted into the aperture in different number of ways, the possibility that the objects would be appropriately oriented by chance varied between the objects. By assuming that all horizontal orientations are equally probable if chance determined the orientation at touch, it was possible to calculate the probability that the object would be oriented correctly by chance. For each way the object could be fitted into the aperture, the tolerance for judging it to be appropriately pre-adjusted was 60º (±30º). Thus, because the object with the square cross-section fit the aperture in at 4 different orientations, the total tolerance was four times 60º, that is 240º or 2/3 of a full rotation. Thus the calculated chance probability was 67% in this case. The equilateral triangle fit the aperture at 3 different orientations and the chance probability is thus three times 60º that is 180º or half a rotation. Thus the calculate chance probability was 50% in this case. The rectangular and ellipsoidal objects only fit at two orientations and the chance probability of orienting them appropriately is therefore 33%. Finally, the two triangular forms where the sides were unequal only fitted at one orientation and the chance probability of orienting them appropriately is 17%. In order to evaluate the infants' ability to pre-adjust the horizontal orientation of the objects to make them fit the apertures, the random probabilities was subtracted from the obtained percentages. The corrected percentages are shown in Figure 8. A split-plot factorial ANOVA with Objects (6) as within and Age (4) as between subject variable was used to test the tendency to pre-adjust the orientation of the objects to fit the apertures. The cylinder shape was not included in this analysis because it did not require any adjustments of the orientation its cross-section to fit into the aperture. Significant main effects were found for both Object ($F(5, 315)= 4.776$, $p < 0.000$, $\eta^2 =0.07$) and Age ($F(3, 63) = 61.49$, $p < 0.000$, $\eta^2 = 0.745$) and a significant interaction between Object x Age ($F(15, 315) = 2.167$, $p < 0.01$, $\eta^2 = 0.093$). The average pre-adjustments for the 22- and the 26-month-olds were significantly above chance but not the ones for the 14- and 18-month-olds. It can be seen from Figure 8 that the tendency to make pre-adjustments of orientation were essentially absent for the 14- and 18-month-old children. Bonferroni adjusted post hoc tests of pre-adjustments of specific objects showed that the 14-month-olds made no pre-adjustments or made systematically wrong pre-adjustments, that the 18-month-olds pre-adjusted the equilateral triangle to a significant degree but none of the other objects, that the 22-month-olds pre-adjusted all objects except the square and elliptic ones, and that the 26-month-olds did it for all objects.

------------- Insert Figure 8 about here ----------------

The duration of the approach

The youngest children used more time to transport the objects to the aperture box, and tended to make more adjustments and changes underway. Figure 9 illustrates the transport time for each of the objects at each age. A split-plot factorial ANOVA was used to test the results with Object form (7) and Presentation mode (2) as repeated measurement variables and Age (4) and Sex (2) as between subject variable. As the Mauchly's Test of Sphericity for homogeneity of covariance was found to be significant, ($p < 0.001$), the more conservative test, Greenhouse-Geisser, was used. Main effects were found for Presentation mode ($F(1, 59) = 10.96$; $p < 0.002$, $\eta^2 = 0.157$) and Age ($F(3, 59) = 8.23$; $p < 0.001$, $\eta^2 = 0.295$), but there was no significant effect of Object form, ($F(3, 150) = 1.2$) and none of the simple interactions were statistically significant (for all of them $p > 0.15$). The Bonferroni adjusted pairwise comparisons show that there are significant Age-differences between the 26-month-olds and all the other age groups, but that the other age groups did not differ between themselves. The task was performed equally fast by the boys and girls ($F(1, 59) = 2.116$; $p = 0.15$) and there was no interaction between sex and the age of the children ($F(3, 59) = 0.104$; $p = 0.9$).

------------------------ Figure 9 --------------------------

Duration of continued attempts to insert the object after touch

After the first touch down on the aperture, most infants continued to try to get the object into the aperture. When they failed they often tried to use brute force. The duration of these attempts reflect the difficulty of the task and the persistence of the attempts. Mean duration was calculated for both the successful and the unsuccessful attempts.This is illustrated in Figure 10. The successful attempts are shorter on the average than the unsuccessful ones because the successful attempts end when the object is inserted while the unsuccessful attempts goes on until the infant gives up. A split-plot factorial ANOVA was used to test the duration of all attempts with Object form (7) as repeated measurement variable and Age (4) and Sex (2) as between subject variables. Main effects were obtained for Object form ($F(6, 354) = 17.064$; $p < 0.001$, $\eta^2 = 0.224$) and Age ($F(3, 59) = 5.366$; $p < 0.002$, $\eta^2 = 0.214$) and the interaction between them was also significant ($F(18, 354) = 3.490$; $p < 0.001$, $\eta^2 = 0.151$).There was no main difference in how long girls and boys persisted in trying to solve the problem ($F(1, 59) = 0.014$; $p = 0.9$), nor was there an interaction between Age*Sex ($F(3, 59) = 1.476$; $p = 0.2$).

------------- Insert Figure 10 about here ----------------

Finally, as can be seen in Table 3, the proportion of successful insertions did not increase linearly with time. On the average, 83% were accomplished after 5 s and 96% after 10 s. There were no differences between age groups. Thus, at all ages, the successful insertions were concentrated to the first few seconds after touch. This can also be seen from Figure 9. If they failed to insert the object the 22-month-olds continued trying, on the average, for 16 s and the 26-month-olds for 12 s. Thus the number of successful insertions did not increase linearly with age.

------------- Insert Table 3 about here ----------------

Discussion

The present study demonstrates that the ability to relate objects to each other undergoes dramatic improvements during the second year of life. As it is often the case with new emerging skills, the infants were extremely motivated and challenged by the spatial puzzles presented. This was also valid for the youngest infants studied. Although the experiment included 28 trials, the 14-month-olds completed 19 (69%) of them in spite of the fact that they only succeeded in 1 out of 3 of these trials. When failing they even tried brut force. However, the many failures tended to make them less motivated towards the end of the experiment and that is probably why they completed fewer trials than the 26-month-olds who completed 27 out of the 28 trials (97%) and succeeded in 4 out of 5 of these.

Even though all infants understood the task and moved the objects to the aperture in a majority of trials, the youngest infants had little understanding of how to orient the objects in order to make them fit into the aperture. Even when they placed the object with its longitudinal axis oriented horizontally over the hole, they often did not realize what was wrong and instead tried to press the object through the lid. Clearly, they lacked an understanding of the spatial relationship between the object and the aperture. In contrast, the 26-month-old infants moved the objects into a vertical position before or during the approach of the hole and turned the objects appropriately before the hand arrived at the lid. What characterizes the development between these two endpoints?

First, the results show that the infants could not solve the problem of inserting the object into the aperture by just moving it around. Success was associated with appropriate pre-adjustments before the hand arrived with the block to the aperture. Such pre-adjustments require the child to somehow imagine the goal state of the action before it is carried out. The results show how these pre-adjustments become more sophisticated with age. They were almost totally absent in the 14-month-old infants, whose manipulations were more exploratory than functional. While moving the blocks to the aperture box, they turned or rotated them in various ways, moved them from one hand to the other, and had a higher tendency than the older infants to take them to the mouth or move them closer to look at them before transporting them to the lid. An illustration of how little they understood of how to orient the objects in order to insert them into the aperture is the fact that they did not systematically raise up the objects lying down and in about a quarter of the trials with objects standing up, they were turned down.

The 18-month-olds turned up some of the horizontally placed objects but not others (see Figure 6). The ones that were turned up less often had an asymmetrical cross section and they were presented with the broadest dimension oriented vertically. The results indicate that it was not the asymmetry of the cross section itself that made the children inclined to place them horizontally on the lid. The elliptic cross-section was as asymmetrical as the rectangular cross-section but could not be presented with its widest cross section in a vertical orientation. The performance on these two blocks was very different. The block with the elliptic cross-section was raised up significantly more often than the one with the rectangular cross section (See Figure 6). Failing to rise up the horizontally placed object was not a pure motor problem. The square object was not easier to grasp and transport than the rectangular object, but it was turned up in a vertical position significantly more often (80% of the trials compared to 40). Thus it seems as if the subjects had a tendency to believe that the asymmetrical blocks presented horizontally with the broadest side facing up would fit into the aperture that way, although the length of the block was clearly longer than the widest dimension of the aperture (7 cm compared to 4 cm). The children might have followed the rule that any object with a distinct vertical dimension would fit into the aperture in that way. These results remind of DeLoache et al. (2004) findings that 1.5- to 2.0-year-old children tried to get into toy cars and slide in miniature slides. It is as if they understood the goal of the tasks but were unrealistic about how to implement them.

The 22-month-old children systematically raised up the horizontally placed objects when transporting them to the aperture. They also showed a tendency to make horizontal adjustments. As a result, the number of successful insertions into the aperture increased dramatically as can be seen in Figures 5a and 5b. This indicates that the 22-month-old infants had an idea of how to solve the problem of getting the object into the aperture. The 26-month-olds solved this problem in a systematic and efficient way by pre-adjusting the orientation of the blocks in the vertical as well as the horizontal dimensions. The 26-month-old infants only failed when trying to insert the horizontally placed object with unequal sides into the aperture. This object only fitted into the aperture in one of the two vertical directions. It seems that not even the oldest infants in the study realized what went wrong when they turned this object up in the wrong direction.

The 14- and 18-month-old children seldom made appropriate pre-adjustments, and when they did, they were as often successful as unsuccessful with inserting them into the aperture. In contrast, the 22- and 26-month-olds were nearly always able to insert the objects after appropriate pre-adjustments (see Figure 7). Furthermore, the inappropriate pre-adjustments rarely resulted in successful insertions at any age. This demonstrates that pre-adjustments are necessary for solving the problem in a consistent way. Especially the older children in the study kept on trying to insert the object for a long time before giving up. It was as if they believed that they were going to succeed if they were persistent enough. Figure 9 shows that the 22-month-olds, for instance, continued trying for 16 s on the average. However, these attempts were not very successful. They only resulted in a few additional successful solutions. Independent of age, 4 out of 5 successes was performed during the first 5 s of a trial (see Table 3).

In conclusion, the results suggest that the object-aperture problem is being solved during the 2nd year of life. This achievement is the end point of several important developments that includes motor competence, perception of the spatial relationship between the object and the aperture, mental rotation, anticipation of goal states, and an understanding of means-end relationships. These abilities are not independent of each other in a task like this and cannot be totally separated. Motor competence is expressed in actions and actions rely on spatial perception and anticipations of goal states. The children in the present study had no problems with grasping and handling the objects. Some of the youngest infants had some minor problems with rotating the objects while transporting them to the aperture and with passing them from one hand to the other, but it appears that this was not the delimiting problem encountered. On the contrary, the greatest improvement in the number of successful insertions occurred at the age when infants began to show significant pre-adjustments of object orientation, that is, at 22 months.

It is a paradox that while infants, when reaching for an object, adjust the orientation of their hands to the orientation of the object from around 5–6 months of age (Lockman, Ashmead & Bushnell, 1984; McCarty, Clifton, Ashmead & Goubet, 2001; von Hofsten & Fazel-Zandy, 1984), they do not solve the aperture problem until they are almost 2 years of age. We think that this large difference in age between the mastery two such apparently similar spatial tasks is a function of several different factors. First, to succeed with the present task, the infants must understand the relationship between the 3D form and the 2D aperture. Secondly, in reaching for an object it is the posture of the hand that has to be adjusted, while in the present task it is an object that has to be adjusted to another object (the aperture). Finally, one must anticipate how to move the object in order to make it fit into the aperture. This entails imagining different future positions of the object, i.e., mentally rotating it.

The results indicate that a pure feedback strategy does not work for this task. The infants need to have an idea of how to reorient the objects before adjustments are done. Such an idea can only arise if the infants can mentally rotate the manipulated object into the fitting position. The ability to imagine objects at different positions and in different orientations greatly improves the child’s action capabilities. It enables them to plan actions on objects more efficiently, to relate objects to each other, and plan actions involving more than one object. Earlier studies of mental rotation have typically used pictures of 2D or 3D objects that are to be mentally repositioned and matched with pictures of one or several alternative choices (Kosslyn et al., 1990; Marmor, 1975). Such tasks are not very suitable for young children and mental rotation tasks have typically been used on school children and adults. The present task shows that mental rotation is expressed in tasks where one object has to be fitted into another and this opens up for studies of the ontogeny of mental rotation skills.

The present results demonstrate no sex differences. The girls performed as well as boys and they both performed the task equally fast. In an earlier study on 7-year-old children's mental rotation Grimshaw et al. (1995) found a weak relationship between ability and prenatal testosterone levels expressing itself in faster performance by girls who had had higher prenatal testosterone levels than by girls who had had lower levels. The present results indicate that the result obtained by Grimshaw et al. (1995) does not originate in a hormonal triggered genetic advantage in prenatal development. If so, boys should be expected to have solved the fitting task better than girls. Thus, the effect obtained by Grimshaw et al. (1995) is probably only indirectly related to mental rotation abilities..

In the past, studies of infants' spatial cognition has primarily been focused on the ability to relate oneself to the surrounding space, for instance, how the representation of space changes from an egocentric to an allocentric one (Quinn, 1994; Klatzky, 1998). The present study shows that during the second year of life there is also a dramatic development of the spatial skill that enables infants to relate different objects to each other. In addition, infants are challenged and highly motivated by such tasks. Thus Bayley's (1969) intuition was well founded when this task was included in her test. As was shown, however, much more information about infants spatial cognition can be extracted from tasks like this, than a simple score of whether they succeed or not.

A note on laterality

Although a majority of the parents showed ignorance of the child's handedness, the results of the present study show that the children were rather consistent in their choice of hand. The right hand was used predominantly. The reason why parents were uncertain of their children's handedness are probably because handedness fluctuates with the difficulty of the task (Fagard & Lockman, in press). When the task is easy, there is a greater probability that either hand will be used (Fagard & Marks, 1998). When it is a new or complex as in the present experiment, children use their preferred hand to a greater extent. Furthermore, these fluctuations in hand preference are also an outcome of other developing skills. Infants become less lateralized when they begin to crawl, and in non-crawlers handedness does not fluctuate as much as in crawlers. In a study with different grasping techniques, Fagard and Lockman (in press) found that when grasping involved bimanual manipulation, handedness was more apparent than for simple grasping. Postural development also explains changes in one- versus two handed reaching strategies, facilitating simple- versus bimanual reaching in different ages.

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Table 1.

Percentages successful insertion of blocks averaged over the vertical and horizontal presentations in the different conditions. The data from the 12-month-olds is only based on 12 of the 22 infants in this group. There were 17 16-month-olds and 14 20- and 24-month-olds.

Age	Cylinder	Cube	Square object	Triangular block
14	*74*	*17*	*3*	*2*
16	*95*	*63*	*38*	*22*
20	*100*	*75*	*73*	*60*
24	*98*	*82*	*82*	*69*

Table 2

The percentage appropriate pre-adjustments of the orientation of the different objects before the hand arrived with them to the aperture-box for the different age groups in the study. a) Objects presented standing up b) Objects presented lying down

Table 2a

Age	Cylinder	Square	Equilateral	Rectangular	Ellipsoid	Isosceles	Right-angled
14	*71.50*	*39.50*	*11.50*	*11.50*	*0.00*	*4.00*	*3.50*
18	*97.00*	*73.50*	*69.00*	*27.00*	*31.00*	*26.50*	*26.50*
22	*97.00*	*65.00*	*70.50*	*50.00*	*35.50*	*38.30*	*64.00*
26	*100*	*97.50*	*92.00*	*81.50*	*84.00*	*76.50*	*60.50*

Table 2b

Age	Cylinder	Square	Equilateral	Rectangular	Ellipsoid	Isosceles	Right-angled
14	*62.50*	*6.50*	*6.50*	*0.01*	*0.01*	*0.01*	*0.01*
18	*82.50*	*41.00*	*50.00*	*0.01*	*14.50*	*9.00*	*6.00*
22	*91.00*	*35.50*	*50.00*	*14.50*	*23.50*	*9.00*	*9.00*
26	*97.50*	*97.50*	*88.00*	*47.50*	*73.50*	*31.50*	*37.00*

Table 3

Percentages of the successful insertions accomplished after 5 and 10 s for the different age groups in the study.

	14 months	18months	22 months	26 months	tot
5 s	81	86	79	87	83
10 s	97	95	94	97	96

Figure captions

Figure 1. The experimental set-up with a subject, his mother, and the experimenter.

Figure 2. The different objects used in the experiment

Figure 3. The coding of the vertical, and horizontal pre-adjustments.

Figure 4. The proportion of right-handed reaches performed by the subjects in the different age groups.

Figure 5. The percentage successful insertions of the different objects into the aperture for the different age groups. *a*. Objects presented standing up *b.* Objects presented lying down

Figure 6. The percentage appropriate vertical pre-adjustments of the different objects presented lying down as a function of age.

Figure 7. The tendency of appropriate pre-adjustments to be followed by successful (filled circles) and unsuccessful (filled squares) insertions into the aperture, and the tendency of inappropriate pre-adjustments to be followed by successful insertions (unfilled squares).

Figure 8. The percentage of appropriate horizontal pre-adjustments as a function of age of the objects presented standing up and those that were raised up of the ones presented lying down. The probabilities of getting the objects correctly oriented by chance are subtracted from the obtained percentages.

Figure 9. Transport time to the aperture box for the objects presented standing up and lying down as a function of age.

Figure 10. The duration of the successful (circle) and unsuccessful (square) attempts to insert objects into the aperture after the hand arrived at the aperture-box as a function of age.

Figures

Figure 1.

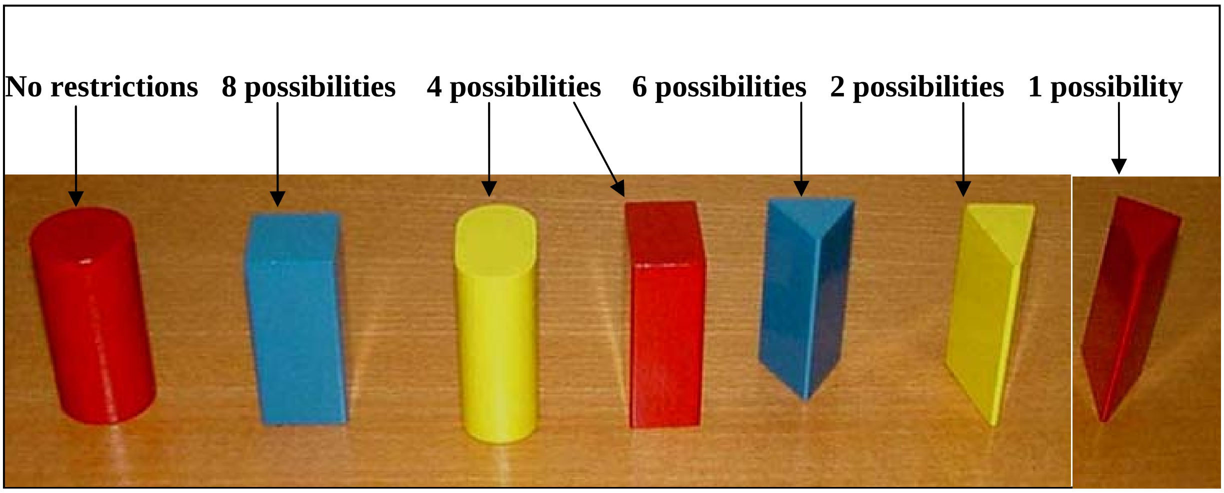

No restrictions
8 possibilities
4 possibilities
6 possibilities
2 possibilities
1 possibility

Figure 2.

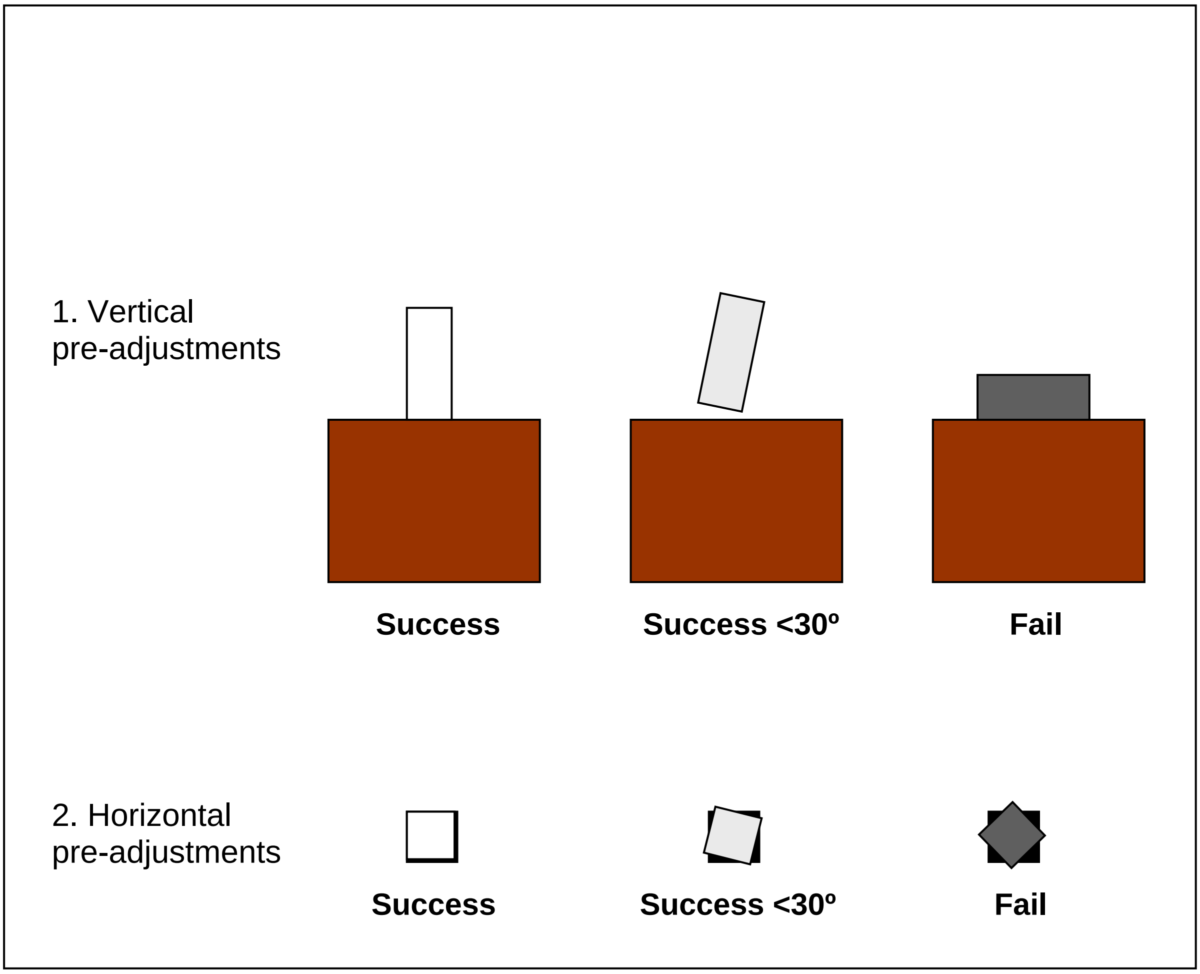

1. Vertical
pre-adjustments
Success
Success <30º
Fail
2. Horizontal
pre-adjustments
Success
Success <30º
Fail

Figure 3.

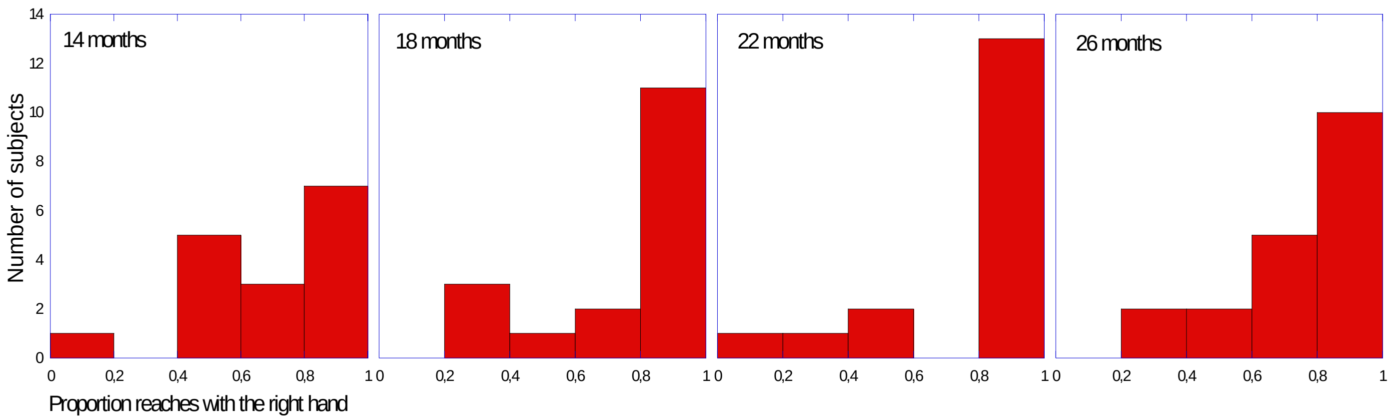

14 months
18 months
22 months
26 months
Number of subjects
0
2
4
6
8
10
12
14
0
0,2
0,4
0,6
0,8
1
Proportion reaches with the right hand

Figure 4.

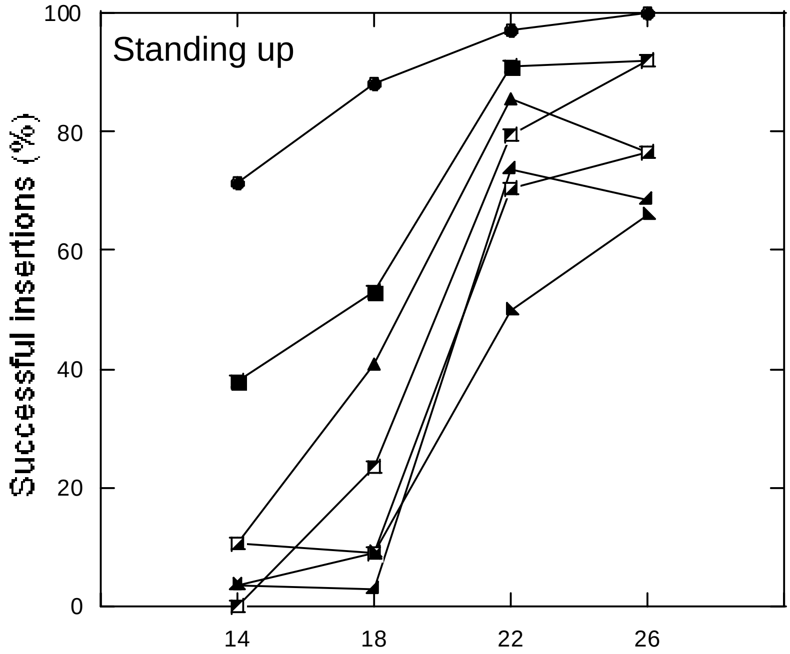


Figure 5a.

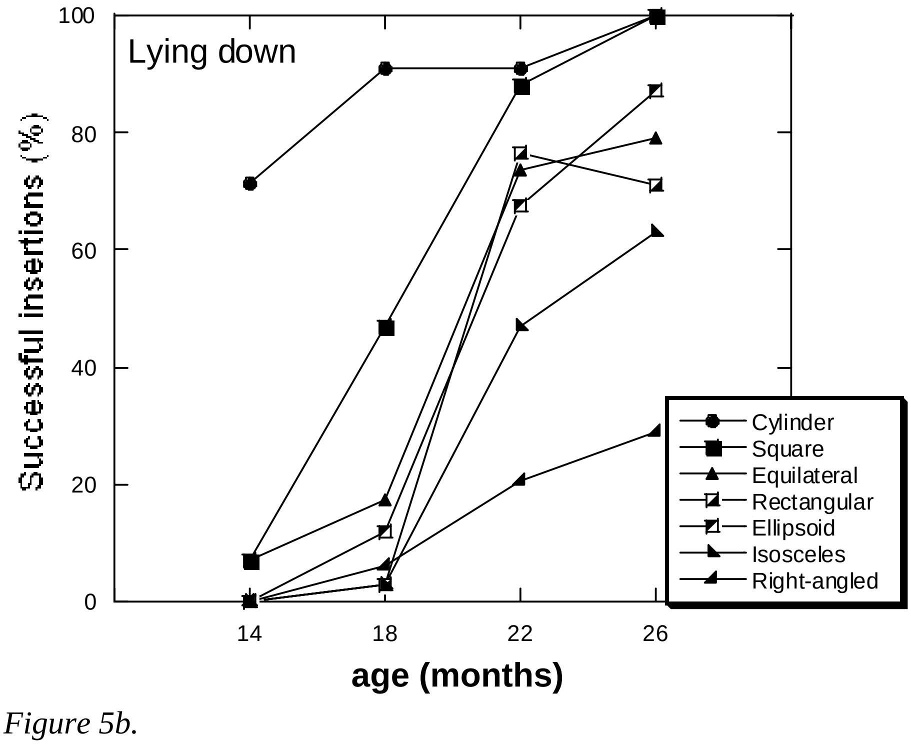


Figure 5b.

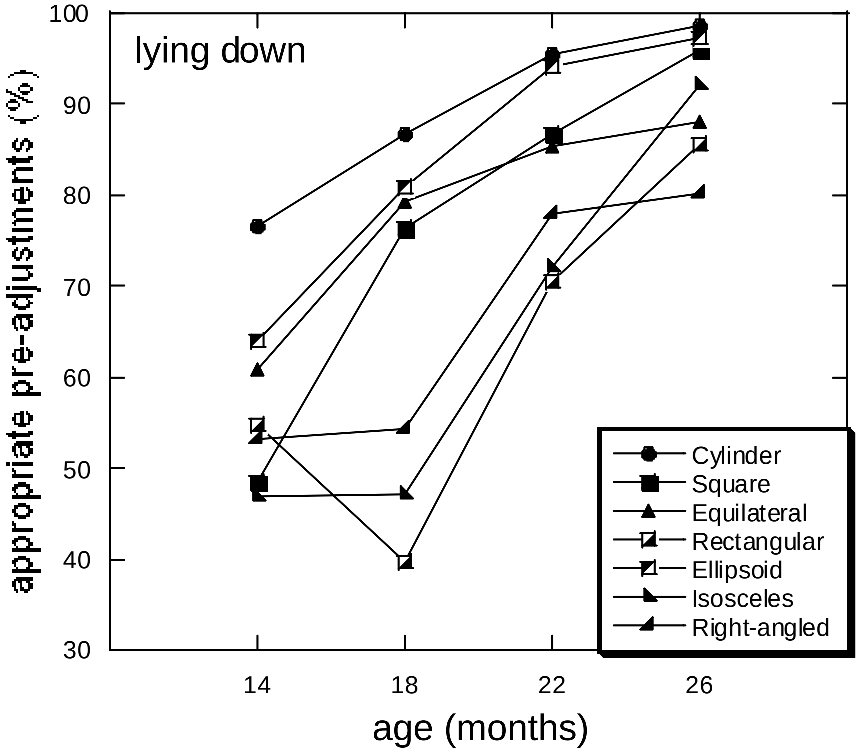

lying down
appropriate pre-adjustments (%)
100
90
80
70
60
50
40
30
14
18
22
26
age (months)
Cylinder
Square
Equilateral
Rectangular
Ellipsoid
Isosceles
Right-angled

Figure 6.

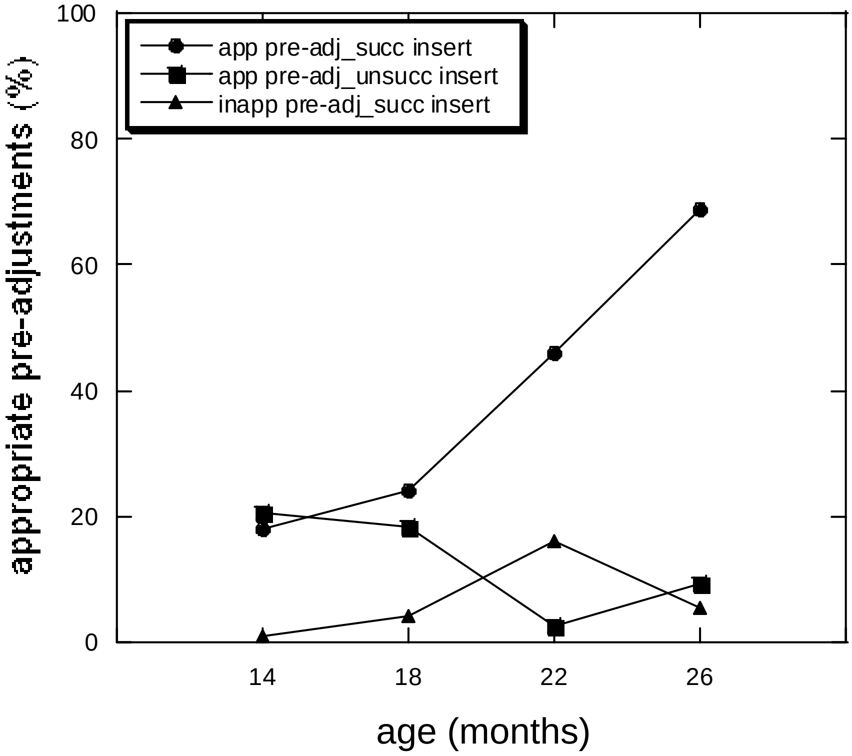
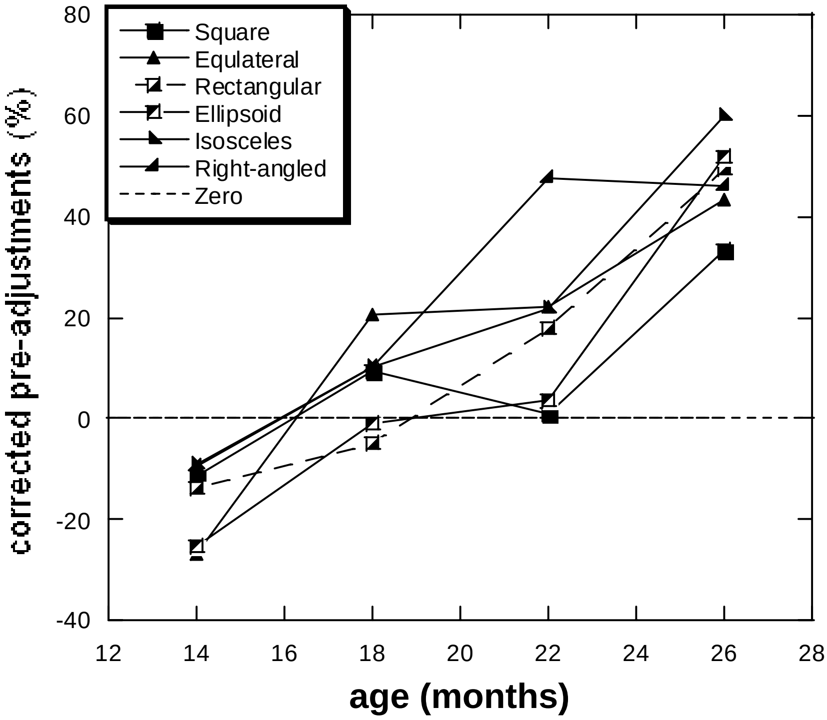

100
80
60
40
20
0
app pre-adj_succ insert
app pre-adj_unsucc insert
inapp pre-adj_succ insert
appropriate pre-adjustments (%)
14
18
22
26
age (months)

Figure 7.



Square
Equlateral
Rectangular
Ellipsoid
Isosceles
Right-angled
Zero
corrected pre-adjustments (%)
80
60
40
20
0
-20
-40
12
14
16
18
20
22
24
26
28
age (months)

Figure 8.

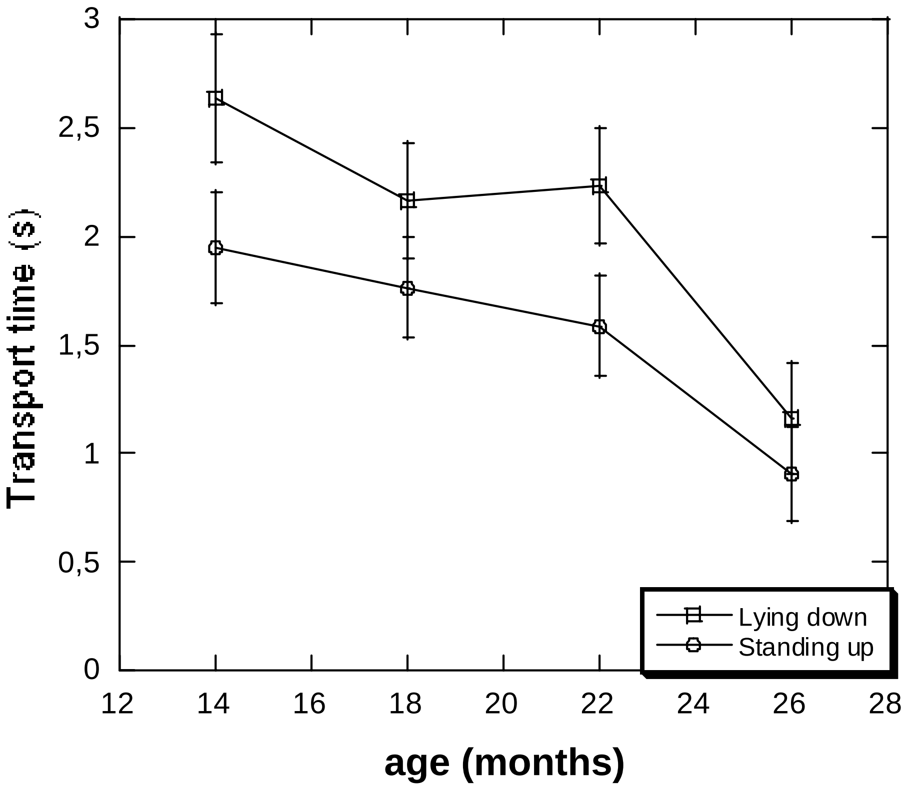
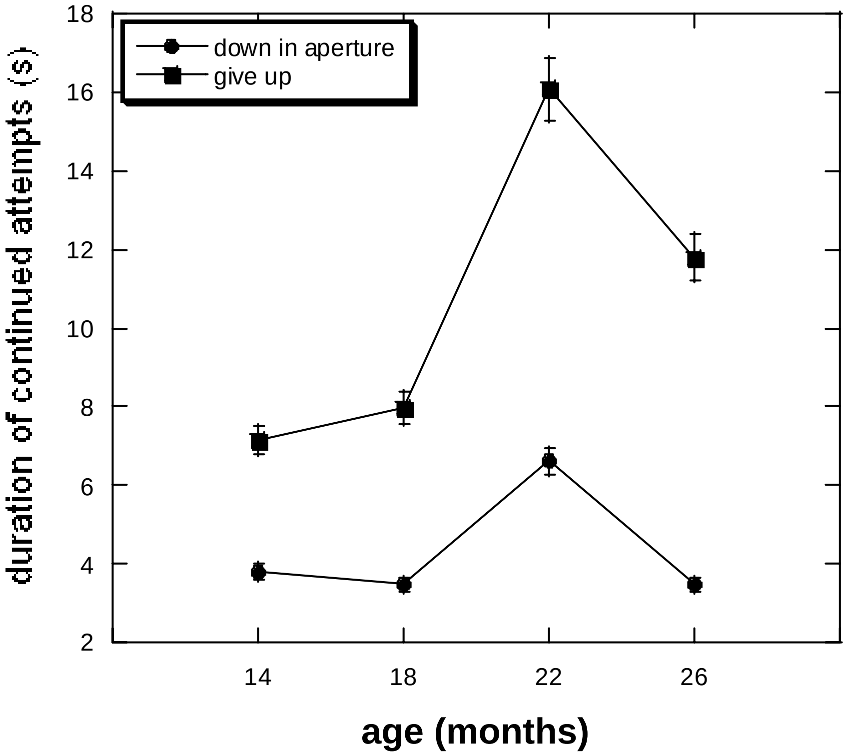

Transport time (s)
age (months)
Lying down
Standing up
3
2,5
2
1,5
1
0,5
0
12
14
16
18
20
22
24
26
28

Figure 9.



down in aperture
give up
duration of continued attempts (s)
18
16
14
12
10
8
6
4
2
14
18
22
26
age (months)

Figure 10.