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Fitting Objects Into Holes

On the Development of Spatial Cognition Skills

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Abstract

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Children's ability to manipulate objects is the end-point of several important developments. To imagine objects in different positions greatly improves children's action capabilities. They can relate objects to each other successfully, and plan actions involving more than one object. We know that one-year-olds can insert an object into an aperture. Earlier research has focused on the start and goal of such actions, but ignored the way in between. This thesis shows that children are unable to fit an object into an aperture unless they can imagine the different projections of the object and rotate it in advance. The problem of how to proceed with an object-aperture matching was studied in 14- to 40-month-old children with a box, different holes and a set of fitting wooden blocks. Study I focused on how to orient a single object to make it fit. Studies II and III added a second object or aperture, introducing choice. In Study I there was a huge difference between 18 and 22 months in solving the fitting problem. Successful insertion was related to appropriate pre-adjustments. The older children pre-adjusted the object orientation before arriving at the aperture(s). The younger used a feedback strategy and that did not work for this task. To choose was more difficult than expected; one must not only choose one alternative, but also inhibit the other. Fifteen-month-olds were unable to choose between sizes and shapes, 20-month-olds could choose between sizes, 30-month-olds could choose between sizes and shapes, but not even 40-month-olds could choose between objects with different triangular cross-sections. Finally, the relationships between an object and an aperture, supporting surface or form were investigated. When comparing tasks requiring relationships between an object's positive and an aperture's negative form, between a 3D and a 2D, and between two 3D-forms, we found that the main difficulties is relating positive and negative form.

Keywords: toddlers, action planning, manipulation, means-end relationships, mental rotation, choice, positive-negative form

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List of Papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

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 - II Örnkloo, H. & von Hofsten, C. (In press). Young Children's Ability to Solve Spatial Choice Problems.
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- Örnkloo, H. & von Hofsten, C. (Manuscript in preparation). Young Children's Understanding of Size Relations.

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Introduction

Fitting objects into holes

When we drop a letter in the mailbox we do it almost automatically, without reflecting on how the action is done. Since we have been exposed to similar situations before, we do not consider the task to be particularly tricky. Before performing the physical action, we form a plan of how to mentally rotate the letter on the way to the box, the intended goal. When our hand holding the letter finally arrives at the box, we do an always perfect insertion (Munakata 1998; Atkinson 2000; 2006). If we have a letter that is much too large for the slot, we do not even try to insert it. In our minds we have already compared the slot to the letter, deciding that the letter's circumference is too large to fit in the slot. While adults insert objects into apertures without so much as reflecting, the difficulties and repeated failures young children face when they manipulate objects can be striking. Researchers have long proposed a mismatch between children's and adults' representations of objects (Piaget 1952). Looking at the matter more closely, the task of inserting an object into an aperture is not so easy after all. It requires processes that cause difficulties for adults as well as children that will be discussed below.

Although some animals use simple tools, the human is unique in utilizing complex tools to expand manipulation possibilities (Shmuelof and Zohary 2005). Inserting a letter into a mailbox, or doing other similar everyday activities, provides a good example of the sort of new situations human children are exposed to when acting on the environment that surrounds them. The ability to solve such problems reflects infants' development of spatial perception and mechanical cognition. By encouraging children to insert objects into apertures in different ways, we are able to study their development of motor competence as well as their perceptual and cognitive capabilities. This achievement is the end point of several important developments that include motor competence, perception of the spatial relationship between object and 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 problem with fitting objects into holes

At the end of the first year, infants start to think about how different objects are related to one another (Hayashi and Matsuzawa 2003). They love to pile blocks, put lids on cans and insert objects into apertures. Through these activities, the child learns to plan actions that involve more than one item. The ability to solve such problems reflects the child's spatial, perceptual and motor development. When children can imagine objects in different positions and orientations, we know that their ability to act improves drastically. Still, the underlying representational abilities impelling this development, and the cognitive problems children must overcome, are poorly understood. The present thesis aims to contribute to this understanding through studies of children's developing abilities to fit blocks into apertures.

Fitting experiments are more complicated than grasping experiments. To succeed with a grasping experiment the hand must pre-adjust to the physical aspects and orientation of the object, and then close around it (von Hofsten and Rönqvist 1988; McCarty and Ashmead 1999; McCarty, Clifton et al. 2001; Oztop, Bradley et al. 2004). In fitting objects into holes, the object must be used as an instrument on another object (Connolly and Dalglish 1989; McCarty, Keen et al. 2001). In addition to perceiving and manipulating the object, one must know what the object shall be used for and how it will be used, that is, the affordance of the object (Gibson 1977). The goal of the action must be clear. In a box-aperture experiment, children must comprehend how the three-dimensional (3D) object is related to the two-dimensional (2D) aperture. Further, they must mentally rotate the object in an appropriate way so that it fits. This demands careful planning (Case-Smith 1995). At the age of about one, children begin to be interested in the problem of how to get an object into an aperture (Gesell and Thompson 1934; Bayley 1969; Hayashi and Matsuzawa 2003; Hayashi 2007). However, they do not yet know how to do it (Meyer 1940; Piaget and Inhelder 1956; McKenzie, Slater et al. 1993; McCarty, Clifton et al. 1999). Piaget and Inhelder (1956) claim that children do not develop an understanding of the relationship between objects until three years of age, but act more instinctively. If the children must choose between two objects, the problem is possibly even greater. Not only do they have to mentally rotate and predict the position of the object, but they must also exclude one object in favor of another.

Children's fascination for fitting objects into holes

Toy manufacturers have long exploited children's fascination for fitting tasks. Such actions have also been used in intelligence tests for children (Bayley 1969; Kelly-Vance, Needelman et al. 1999; Psykologiförlaget 2004). Mental, motor and behavioral development are examined in children at ages of one to 42 months (Kelly-Vance, Needelman et al. 1999). By observing how a young child inserts objects into apertures and piles objects into towers, one can compare his/her attention, orientation of objects, and control of impulses to that of other children. The Bayley Scales of Infant Development-Second Edition (BSID-II) and similar studies have found that children of one year of age manage to insert one object into an aperture (Gesell and Thompson 1934; Bayley 1969; Hayashi and Matsuzawa 2003; Hayashi 2007). It is therefore somewhat surprising that we have not found more systematic studies reflecting this development.

An action cannot take place if the desire does not exist. It is the motive that determines the goal. Adults can perform an uninteresting task for reasons other than desire, but young children cannot be persuaded to perform a task if they think it is boring. The children must be motivated and have an interest in the task if they are to initiate and maintain an action (Passer & Smith; Geen, 1995). One of the most essential motives for a young child is to explore the surrounding world and try to find out what he/she can do to change it (von Hofsten 2007). Increasing the knowledge of the world seems to be rewarding in itself. It was remarkable to see how the children in our studies continued to try even if they could not insert the object into the box. This can be compared to children's stubbornness when they learn to walk, one of the bigger motor changes (Adolph, Vereijken et al. 2003; Garciaguirre and Adolph 2006; Joh and Adolph 2006). Children crawl easily and effortlessly. When they stand up and walk, they fall and hurt themselves (Joh and Adolph 2006). The most simple solution would be to continue to crawl, and the skills needed for crawling are not necessarily the same needed for walking (Adolph, Eppler et al. 1993; Adolph 2002). But since humans walk upright and normally developed children finally learn to walk, they continue trying to stand up and walk, in spite of the inconveniences. It is as if they have a feeling that they will soon know how to walk, and when they rise they continue to practice. This is the most central underlying reason for why development happens (Joh and Adolph 2006), and the same can possibly apply to our fitting studies. As in the walking studies, children are soon going to insert the object. But to finally manage to insert the object they have to practice.

Underlying perceptual development

Perception and discrimination of sizes

Already at five months, infants use visual information to control their hand movements to grasp differently sized objects (von Hofsten and Rönqvist 1988). At nine months, infants adjust the opening of their hand to the size of the target. Although the size adjustments of 13-month-olds seem to be fully developed, they still lack fine-tuning.

Size constancy implies that we perceive an object as unchangeable, though the projection on the retina changes in size (Berk 2006). Some researchers have found that already at one week old, infants can perceive an object's physical size (size constancy) (Slater, Mattock et al. 1990). Others have found that it is not until binocular vision appears, at three months, that infants can identify objects by their physical size (Granrud, Haake et al. 1985). Still others propose that infants are not able to identify objects by their size until 4½ months (McKenzie, Tootell et al. 1980; Wilcox 1999).

To comprehend that a distant object takes up a smaller visual angle than a more near object is an important development for being able to insert an object into an aperture. Since the aperture is further away than the object, it takes up less visual angle than the object does. Some conditioning experiments have studied this: Piaget and Inhelder (1956) claim that by the age of six months, children can perceive size irrespective of distance. The authors suggest that this is a continuous process. It is true that infants can be aware that a distant object takes up less visual field than a nearer object, but they do not know how much less. To learn this, they must actively examine the environment. This is crucial for determining size, form and distance more precisely. Other studies have found that already at three months, infants perceive equally large objects as having the same size when they are at different distances (Bower 1966). Spelke, Breinlinger, Macomber and Jacobson (1992) suggest that four-month-old infants can compare the width of a ball to the width of an opening and judge whether the ball can fit through the opening. At 5½ and 6½ months, infants are able to reason about physical information to identify the size of objects, having learned that stationary objects are displaced farther when hit by a larger object as opposed to smaller moving objects.

According to Piaget and Inhelder (1956), not until three years of age a child's proportional scheme is completely developed. They assert that at the beginning of the pre-operational stage, at about two years, children are

unable to match objects, but act more on intuition. They claim that children can match objects of various sizes by 30 months, but are not fully clear about the relationship between objects.

In a study on perception of size difference in young children, DeLoache, Uttal and Rosengren (2004) claim that the usual interdependence between perception and action occasionally collapses in young children. Familiar objects sometimes have wrong proportions when used in action. Eighteen to 30-month-old children were presented with small replicas of larger objects. They then tried to slide down a miniature slide, step into a toy car, or sit on a miniature chair, actions distinctly separated from pretend play behaviors. However, children adapted their movements to the actual size of the toys, for example precise adaptation of the hand to the miniature car's door handle. These scale errors may be an immature integration of the action-perception system, a combination of undeveloped inhibitory control, and the discoordination of two visually functional systems that process different information.

A countering article proposes two explanations of this size error data; the planning-control model and the perception-action model, which emanate from the visual system (Glover 2004). In the first model, action planning and control are said to go to separate locations in the brain. Movements are gradually adjusted, meaning that the child's movements are adjusted to the actual size of the toy on the way. In the second model, planning and control are said to go to the same location. Movements directed towards the toy are appropriately scaled from the start. As a critic of the study of DeLoache et al. (2004), one could presume that the children's actions are over-interpreted as serious actions. According to Piaget (1952), children do not start to engage in pretend actions until they can form mental representations, at about two years. Rakoczy and Tomasello (2006) claim that children under five years are unable to pretend, as pretending has to be done knowingly and intentionally. It could also be that children imitate the actions they frequently experience in reality. They might find that it is impossible to sit on a miniature chair, but they want to see the consequences all the same through a sheer spirit of discovery. Another guess is that the behavior of play has to do with immature inhibition (see the subsequent section Choosing between two objects).

Development of shape perception

As the manipulation of objects demands perception of size and form, we must ask ourselves when these abilities develop. Even though objects have permanent structures, the images we have on the retina are constantly

changing (Berk 2006). Similar images can appear to be different, and different images can look similar. Objects that are nearer take a larger visual angle than objects that are further away. Perceived colors are ambiguously related to light and wavelengths on the retina. Yet, we perceive objects as unvaried (Williams and Hanson 1996).

How is perception of objects measured in infants, who you cannot communicate with verbally? Turning their gaze toward interesting objects and following them when they move is one of the first actions infants master (Atkinson 2000). Habituation means that a child's interest in an object diminishes if it is shown repeatedly (Slater, Mattock et al. 1990; Slater and Johnson 1999; Atkinson 2000; Slater 2001; Spelke 2002). Our senses react first when the stimulation of the object changes. If a new stimulus is shown and the change is perceived, the infant again looks at it longer. From habituation studies, we know that infants remember what they see and can recognize an object. Studies of habituation suggest that already during the first week of life a form can be perceived as constant although the picture on the infant's retina changes (Slater and Johnson 1999; Slater 2001; Caron, Caron et al. 2007), indicating that knowledge of at least some perceptual laws are innate (see the previous section Perceiving one object in another).

Already from birth, infants can direct their arm toward an object (von Hofsten 1982; van der Meer 1997), but it is not until four or five months that can they grasp it (von Hofsten and Rönqvist 1988). When infants are going to grasp, they must plan their actions. In this way they can interact with the world. Reaching studies give a good impression of how children's perception and cognition develop. As is the case with studies of habituation, grasping studies can be used to measure object perception.

Adults can recognize an object by looking for uninterrupted form, surface and color. However, infants do not categorize stimuli like adults do. Studies using habituation have shown that infants younger than two months are unable to perceive object limits (Johnson 1997; Johnson, Bremner et al. 2002; Johnson 2004). Instead, they identify an object from where it is located and how it is moving. It is not until the object is localized that they can perceive object limits such as form, surface and color (Spelke and Hermer 1996; Jusczyk, Johnson et al. 1999; Johnson and Mason 2002). Piaget (1954) discovered that six-month-olds succeeded in grasping a small object hanging in the air, but failed when the small object was placed on a larger object. Thus, infants perceive an object when it is separated from other objects and when it is placed at another depth. Conversely, they fail to perceive it as a separate object when it is adjacent to another object (von Hofsten and Spelke 1985; Spelke, von Hofsten et al. 1989). Infants are more sensitive to moving objects than to stationary ones. Studies using habituation and preferential looking demonstrate that infants of two months perceive a moving object whose centre part is occluded as one unified object rather than two separate objects (Kellman and Spelke 1983; Johnson and Aslin 1995;

Johnson 1997; Eizenman and Berthenthal 1998). When the object was stationary, in contrast, the infants did not perceive the parts of the object as connected. Gradually, they can perceive object limits and stationary objects, beginning to unite the different parts of the object into a whole. Instead of concentrating on movement, they begin to perceive form, color and surface as adults do (Needham and Baillargeon 2000; Cohen and Cason 2001). Studies have shown that four to five-month-old infants begin to separate different objects by form and size (Wilcox 1999; Needham 2001; Dueker, Modi et al. 2003). From 7½ months they are able to use patterns, and by 11½ months color for differentiate objects (Wilcox 1999). Both age and experience with the task increase their ability to perceive the difference between objects.

Grasping studies have shown that five-month-old infants categorize objects like adults do, that is, they perceive objects as things they can manipulate with unvarying form and exterior limits (von Hofsten and Spelke 1985). According to Poom and Börjesson (2005), adults judge objects according to different sources of information, prior experience and probability assessments. Infants make judgments based on incomplete information (Vurpillot 1968). Moreover, they lack experience. But since infants act surprised when certain characteristics of the object change (Spelke and Hermer 1996), the perception of objects may originate from an innate conception of what an object is (Kellman and Spelke 1983; Kellman 1993).

Researchers have different ideas of how children represent forms. Piaget and Inhelder (1956) argue that early representation of forms was topological. Topology is sometimes called rubber band geometry. A rubber band can be stretched, twisted and deformed, as long as you do not break it. A circle is topologically similar to a square, but not to a figure eight, because you cannot make an eight without breaking the circle. Other researchers suggest that young children initially use template matching for recognition of perceptual patterns such as letters or shapes (Gibson and Gibson 1962; Anderson 1985). If this is the case, all forms should be equally easy to discern. A pair of shapes that look similar should be as easy to separate as a pair of shapes that look dissimilar. Even others claim that children form schemas on the basis of feature analysis of visual forms (van Hiele 1986; Clements and Battista 1992; Clements, Swaminathan et al. 1999). While these schemas are developing, children may attend to a subset of the visual characteristics of a shape and are thus unable to identify and distinguish among many common shapes or distinguish among figures in the same class. Children should thus find it harder to discriminate between similar shapes than shapes that have a clear distinction. Gradually, children begin to define shapes visually according to their appearance (van Hiele 1986; Clements and Battista 1992). They can think about shapes as wholes, but not about their properties. The preschool child goes from a simpler to a more complicated

way of imagining a square shape: from no dimensions to several dimensions, no matter how the object is rotated.

Comparing different shape dimensions

The sensitivity to binocular disparity emerges at three to four months of age (Atkinson 2000). Before binocular vision appears, it seems impossible to discern 2D objects from 3D ones, although the world is constructed of 3D objects. Children's understanding of objects and space emerges gradually under their development (Piaget and Inhelder 1956). Some studies show that children of two years recognize a real object from a picture even when they have never seen it in real life (Hochberg and Brooks 1962; Daehler, Perlmutter et al. 1976; Harris, Kavanaugh et al. 1997; Tomasello, Striano et al. 1999; Striano, Rochat et al. 2003; Younger and Johnson 2004). Other studies have found that children recognize the relationship between objects and pictures successfully when they are about one year old, but these are 3D models and 2D pictures made for the studies that are simpler than those in the real world (Rose, Gottfried et al. 1983; Skouteris, McKenzie et al. 1992; Younger and Johnson 2006). Rose (1977) found that even six-month-olds are able to relate 3D objects to 2D pictures (see the subsequent section *Perceiving how an object fits in another one*). For an object to be identified, its spatial characteristics must be known, and its different parts must be remembered (Skouteris, McKenzie et al. 1992).

That objects and apertures look different is also a problem. In a way, they are diametrically opposed. While an object takes up a positive space, an aperture takes up a negative space. The negative space of the aperture can be perceived as a background to the surrounding frame (Rock 1983; Palmer 1999; Bertamini and Croucher 2003). As stated in Gestalt therapy, a background is always a part of a figure. If the figure disappears the background is obliterated. If the aperture was like a background, it would be hard to perceive and therefore also hard to remember. Research has shown that apertures are as easy to remember as objects (Rock 1983; Palmer 1999; Bertamini 2006). Even if apertures are neither material nor objects, it is a complex form that has the function of describing forms, and since the shapes of apertures and objects have curvature with opposite polarity they are perceived as having different shapes.

Perception and action

Two visual systems

Apart from analyzing objects, our visual system also prepares us for manipulating them. A documented neuropsychological theory states that when visual information has passed the primary visual cortex (V1) it splits into two pathways, the ventral and the dorsal stream, that process the information differently (Mishkin and Ungerleider 1982; Livingstone and Hubel 1988; Milner and Goodale 1992; Atkinson 2000; Braddick, Atkinson et al. 2003; Atkinson and Braddick 2006). The ventral stream recognizes and identifies forms and objects and has for this reason been called "the what stream" (Milner and Goodale 1992; Milner and Goodale 1995). The dorsal stream relates between perception and action and has thus been called "the how stream" (Milner and Goodale 1992; Milner and Goodale 1995). The dorsal stream prepares manipulatory actions like grasping and reaching (Shmuelof and Zohary 2005). A quite new discovery is the mirror neuron system, which fires both when an action is performed by the individual and when an action is performed by another (Rizzolatti 1996; Rizzolatti and Craighero 2004; Fogassi, Ferrari et al. 2005). It has been found that the mirror neuron system is related to the dorsal stream. With the mirror neuron system as a starting point, Shmuelof and Zohary (2005) carried out fMRI studies with the intent of separating perception and action. The results describe that both the recognition and planning of actions are localized to the dorsal stream of the parietal cortex.

Action planning

Planning is imagining ahead of time a sequence of movements with a specific purpose and goal (Scholnick 1995). A goal-directed action is always planned (Hommel, Müsseler et al. 2001; Umiltà, Kohler et al. 2001; von Hofsten 2004). If our actions were not predictive but instead reactive, we would lag behind the events we want to coordinate with (von Hofsten 2004). The senses are prepared to extract information from our surroundings. The planning of actions is possible because events in the world are regulated by rules and regularities (Gredebäck and von Hofsten 2004). With this knowledge, we can predict the future without being restricted to what is happening right now. Newborn infants are able to orient their face toward a sound and reach their hand toward a target (von Hofsten 1982). Infants use prior information to guide their hands toward their mouth, which is far more

likely to be opened when the hand is aiming toward it than toward some other part of the face (Butterworth and Harris 1994). The fact that the infant prepares itself by opening its mouth indicates that actions are planned and goal-directed; if the opposite were true, the infant would react by opening the mouth after touching it.

Smooth grasping movements require planning. When a series of pictures was shown in a certain order, two- and three-month-old infants learned to move their gaze to where the object would reappear next (Wentworth and Haith 1998). Six-month-old infants reach their hand towards an object and open it in advance, rotate it so that their grasp will fit the object, and begin to close their hand before it arrives at the object (Lockman, Ashmead et al. 1984; von Hofsten and Fazel-Zandy 1984; von Hofsten and Rönqvist 1988; McCarty, Clifton et al. 2001; von Hofsten 2007). Accordingly, this shows that by this age, infants have acquired so much knowledge of an object that they can grasp it. At the same time as they begin to grasp an immobile object, they can catch a moving object (von Hofsten 1980; von Hofsten 1983). To catch a moving object, the grasp movement has to be directed toward a future position of the object. Infants can do this by six months of age (von Hofsten 1980). When it comes to fitting actions, planning is even more essential. When you are going to join two objects successfully, the objects must be positioned and rotated in advance.

The handling of an object depends on the intention of the action (Manoel and Connolly 1998; Claxton, Keen et al. 2003). For example, ten-month-olds reached faster for a ball that they were going to throw into a bucket as opposed to fit into a tube (Claxton, Keen et al. 2003). The first action (although grasping the object) is carried out differently depending on what the subsequent action is. In other words, the planning of the second action begins already during the accomplishment of the first action.

Piaget (1952) asserted that under around eight to twelve months of age, children are incapable of representing objects and experiences. However, in completion and occlusion studies researchers have found that four- to five-month-old infants extrapolate the motion of an object behind an occluder by moving their gaze to the point where the object is going to reappear (Rosander and von Hofsten 2004; von Hofsten, Kochukhova et al. 2007). This indicates that the infants can mentally represent an object during the occlusion intervals, and they can imagine the route of the object in advance. This could be a sign that infants can visualize the path an object takes to the goal. As the children in our studies must imagine the condition of a goal, moreover, the object is going to be invisible at the finishing point, i.e. it is going to be hidden in the box; this is important to us. These studies show that infants' actions are future-oriented. Yet, under six months of age, infants are not capable of planning tasks that are more than simple, known and routine (Wellman, Somerville et al. 1979). For example, four-month-old

infants search where the object disappeared and where they last saw it reappearing.

When preschool children were given the task of comparing two detailed pictures, they neglected much information that school children noticed (Vurpillot 1968). Older children and adults plan their search in steps. One possible reason younger children neglect visual information is that they focus more on the goal of an action than on the procedures (Gergely, Nasady et al. 1995; Meltzoff 1995; Carpenter, Akhtar et al. 1998; Woodward 1998; Csibra, Gergely et al. 1999; Woodward and Somerville 2000; Woodward, Sommerville et al. 2001; Carpenter, Call et al. 2002; Woodward and Guajardo 2002; Csibra, Biro et al. 2003; Somerville, Woodward et al. 2005; Sommerville and Woodward 2005). Still, by the age of six years, when children are asked to describe the path from one place to another, they focus on the goal and not on the route there (Plumert, Pick et al. 1994). It is not until they walk the path themselves, or someone asks them leading questions, that they give clearer directions. Habituation studies have shown that infants react more strongly if the goal, as opposed to the path there, changes (Woodward 1999).

Manipulation of objects

Although grasping movements have been observed in newborns, it is not until they are about four five months old that they successfully grasp objects (von Hofsten and Fazel-Zandy 1984; von Hofsten and Rönqvist 1988). When manipulating an object with the hand, it must adjust to the physical characteristics of the object (like form and size), spatial characteristics (like how the object is oriented) and temporal characteristics (like when you have to close your hand) (Lockman, Ashmead et al. 1984; von Hofsten and Fazel-Zandy 1984; von Hofsten and Rönqvist 1988). By one year of age, children have acquired a number of actions that they use to manipulate objects (Bourgeois, Khawar et al. 2005). Furthermore, different objects are manipulated in different ways. Children feel the surface more on objects that have surface structure than on objects that do not, and they shake or pound more on objects that produce a sound than on objects that do not (Gibson and Walker 1984; Lockman and McHale 1989; Palmer 1989; Bushnell and Boudreau 1993; Molina and Jouen 1998; Lockman 2005). Bourgeois et al. (2005) suggest that future development that demands more complex abilities originates from this early adaptation of different objects. While the ability to manipulate objects is developing, spatial perception, control of posture and gaze and the motivation to grasp improve. The difference between arm and hand become more apparent. Still, it is not until children are about one year old that they begin to understand the relationship between objects. Earlier,

they have perceived objects as a part of themselves (Piaget 1952). Now, they begin to perceive the space of different objects in the room in relation to each other, and treat the objects according to function.

Lockman (2005) suggested that abilities related to object manipulation are the basis for tool use, and makes a developmental distinction between object manipulation and tool use. With his definition, object manipulation is restricted to the relationship between the hand and the object, and the actions concentrating on that very object. With tool use, the subject must not simply direct attention toward an object, but also relate it toward a desired goal, that is, another object or another place. Also, tool use includes a change of the function of arm or hand. A hammer does not only extend the reach of the hand, but transforms its characteristics into a hard, inelastic surface. A spoon transforms the elongated hand to a bowl, in which it is possible to transport fluid.

Mental rotation

Perceiving object in different perspectives

When an object is rotating, the picture on the retina is constantly changing. Rotation can be linked to studies using partly covered objects. As with the object that goes in and out of sight and becomes occluded by closer objects, the whole object is not simultaneously visible. Still, objects are perceived as stable and unchanging rather than constantly changing (Williams and Hanson 1996). Two-month-old infants were presented with an object where the middle was hidden by an occluder (Kellman and Spelke 1983). The authors found that when the object was moving behind the occluder the infants perceived that the object parts belonged together, but when the object was stationary they were unable to see any connection between the parts of the object. That signifies that from two months of age, infants perceive movable, but not immovable, partly hidden objects the same way adults do. Later studies have achieved similar results (Johnson and Aslin 1995; Johnson 1997; Eizenman and Berthenthal 1998).

Perceiving how an object fits in another one

Early in life, infants can perceive that objects are the same from different angles. Our studies treat the relationship between objects; to be precise, at

least two items. And though the objects fit together they look dissimilar, with the positive space of one object and the negative space of the aperture (see the subsequent section Comparing different shape dimensions). The problem is to understand the spatial relationship between an object's 3D shape and the 2D shape of the aperture. To fit an object into an aperture, children must be aware of how they are going to orient the object for it to fit. Researchers have long been of the opinion that mental rotation develops quite late, and that even adults have limitations in understanding mental rotation (Roberts and Aman 1993; Tversky, Kim et al. 1999; Uttal, Gregg et al. 2001). When two objects appear in the same orientation this task is easy, but it is surprisingly difficult and time-consuming when the orientations of the two objects differ, and one must imagine rotations of the 3D object to make it fit the aperture (Massironi and Luccio 1989; Shiffrar and Shepard 1991; Pani 1993). A classical study of object perception and mental rotation says that the greater the angular difference is, the longer time is required to decide whether two objects are identical (Shepard and Metzler 1971; Shepard and Feng 1972). Another well-known study is mental paper-folding, where one must decide if a 2D picture can be folded into a cube (Shepard and Feng 1972). The study demonstrates that the more folding that is required, the longer time it takes. The more spatially complicated a task is, that is to say the more steps you must imagine, the more you have to realize and plan. When adults judge direction, they perform worse when the rotation angle is oblique than when it is vertical or horizontal (Shiffrar and Shepard 1991; Pani 1993; Pani, William et al. 1995; Pani, Jeffres et al. 1996), probably because humans discern the vertical and horizontal in the environment more easily (Howard 1982).

In some cases, children younger than one year can relate 3D and 2D figures. This partly has to do with how the object is presented (see the previous section Comparing different shape dimensions). If the 2D and 3D figures are not rotated in different ways but are presented in the same direction to the child so that their appearance looks similar, it is easier to relate them to each other. Also, the more experience the child has had with objects of a certain class, the easier it is to recognize a similar object (Tarr and Bülthoff 1995; Tarr and Bülthoff 1998).

To fully recognize an object, a child must not only know the spatial characteristics of the object and remember its different parts, but also must know how to identify the appearance transformations during motion (Skouteris, McKenzie et al. 1992). Thus, it is only logical to distinguish an object presented from a familiar angle prior to one presented from a new angle (Piaget 1952; Rudge and Warrington 1991; Tarr and Bülthoff 1995; Tarr and Bülthoff 1998).

Very few studies using mental rotation have been conducted on young children, though some examine the age at which children are able to insert an object into an aperture. Researchers conclude that children are about one

year old when they can insert a simple object, like a ball, into a circular aperture (Gesell and Thompson 1934; Bayley 1969; Hayashi and Matsuzawa 2003; Hayashi 2007). It is not until they are nearly two years old that they can insert a more complicated object, like a cube, into a square aperture (Gesell and Thompson 1934; Bayley 1969; Geerts, Einspieler et al. 2003). What makes the cube more difficult to fit into a hole than a ball is that the former must be oriented in such a way as to make its cross-section correspond to the orientation of the aperture. These studies mention nothing about how the children behave on the path to the aperture.

Some experiments focus on the adjustments of the hand holding the object before it reaches the aperture though. Ten-month-old-children tried to reach for an oblong object that could only be retrieved through a horizontal or a vertical aperture (McKenzie, Slater et al. 1993). The object was placed at either a right or oblique angle to the aperture. The children could see the relationship between object and aperture more easily, and made fewer errors when the object and the aperture were pointing in the same direction. Furthermore, they seemed to have a hand preference for horizontal orientation. By 12 months, children can insert a ball into an aperture (Gesell and Thompson 1934; Bayley 1969; Achard and von Hofsten 2000; Hayashi and Matsuzawa 2003; Hayashi 2007). However, that does not mean that they pre-adjust the hand to the object at such an early age. Meyer (1940) examined how 18-month to 5½-year-old children solved different spatial tasks by inserting objects into apertures. She found that between 18 and 24 months, children manipulated the objects by feedback. The two and three-year-olds could make some pre-adjustments, but could not always repeat a successful trial. It was not until three years of age that the children understood that they had to pre-adjust the object so that it fit the aperture. In a later pre-adjustment study, children were encouraged to transport a spoon containing applesauce to their mouth (McCarty, Clifton et al. 1999). The handle of the spoon was placed either to the left or the right. If the handle was placed on the reverse side relative to their preferred hand, the problem was greater for the children. Nine-month-olds used feedback, awkwardly turned the handle to eat the food only when the spoon had arrived at their mouth. Thus, the children did not use mental rotation. Fourteen-month-olds used a partially planned strategy: The handle was rotated after the spoon was picked up, but before it had reached their mouth. Nineteen-month-olds picked up the spoon in a way that was fully adjusted to the task, at a much younger age than in Meyer's (1940) study.

Perceiving one object in another

Some cognitive skills emerge earlier, and develop much faster than others (Baillargeon 2004). The core knowledge theory argues that some appropriate knowledge is innate (Spelke 2000; Spelke and Kinzler 2007). Core knowledge theorists suggest that we are born with fundamental cognitive abilities that let us make sense of objects, space, people, movement, actions, and number. This core knowledge underlies everything we learn later in life. Core knowledge theorists lean on the fact that infants comprehend some actions but not others very early in life. Infants understand that objects cannot pass through other objects (Hespos and Baillargeon 2001). In containment studies, 2½-month-old infants looked longer at an event in which an object was placed in a closed box (impossible event), than an event in which an object was placed in an open box (possible event). They were more surprised by the first event than the second, indicating that 2½-month-olds already know that the impossible event violates physical laws. Infants who are five to six months old react when an aperture object is wider than the aperture it is to be inserted into (Sitskoorn and Smitsman 1995; Aguiar and Baillargeon 2002), and 7½-month-olds react when the object is higher than the box in which it disappears (Hespos and Baillargeon 2001).

Mental rotation and sex differences

Adult males have earlier been reported to have an advantage over females in tasks requiring mental rotation (Voyer 1995). This advantage is, however, much less distinct in children, if at all present (Voyer 1995; Roberts and Bell 2002). As proposed by Hyde (2005) and Spelke (2005), adult men and women have equivalent cognitive abilities, but slightly different approaches to cognitive problems that can be solved with multiple strategies. Men and women are apt to choose different solutions, but when they are encouraged to choose one source of information the gender gap of reasoning is narrowed and they tend to perform equally well (Spelke 2005). A few studies have found differences in the preschool years, (1995; Levine, Huttenlocher et al. 1999; DeLoache, Uttal et al. 2004). Grimshaw, Sitarenios, & Finegan (1995) found a weak relationship between seven-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.

Choosing between two objects

Executive control

Planning, mental operations, initiating appropriate actions, selecting relevant sensory information and inhibiting inappropriate actions are the key factors in executive function (Murray, Veijola et al. 2006). Executive function engages the frontal lobes and the prefrontal cortex, which are the last to mature in the brain and continue to develop beyond adolescence and into adulthood.

Very young children cannot concentrate on one task, but direct their attention to what is most interesting and conspicuous at the moment (Luria 1973; Richards and Holley 1999). The infant's original plan of action, for example crawling toward a toy, is interrupted by another interesting stimulus that involves a new plan, which might itself be diverted by another attractive stimulus. During their first year, infants develop an ability to inhibit unnecessary responses to stimuli that have nothing to do with their current plan of action. Their disorganized and accidental behaviors become more flexible and goal-directed. They become more effective in recognizing and following objects that suddenly change direction (Gredebäck, Örnkloo et al. 2006). Through this, they become more goal-directed and can focus on one task, which is necessary if they are to execute a complicated task.

In the sociability process, young children start to proceed from internal to external regulation of conduct (Kochanska, Coy et al. 2001). As indicated by Kopp (1982), children between 12 and 18 months of age become capable of following demands that include initiating, maintaining and ceasing a behavior. At 24 months, children become capable of controlling themselves; they can delay or adjust their behavior when asked, even without supervision. At 36 months they are able to self-regulate, a flexibility for controlling processes that meets changing situational demands. The ability to exclude irrelevant information develops gradually (Durstun, Thomas et al. 2002). A choice experiment demands that you go through all available information before you begin the task. Young children often fail to do this and tend to make decisions based on incomplete information (Vurpillot 1968). When five- to nine-year-old children were to get groceries from a list in a play store, older children more often took time to pause, scan and gather enough information to find the smartest solution while the younger children acted more rashly (Gauvain and Rogoff 1989; Szepekouski, Gauvain et al. 1994). To make a choice without complete information can be

related to the studies by Keen and colleagues (Claxton, Keen et al. 2003; Keen 2005; Kloos and Keen 2005; Kloos, Haddad et al. 2006; Shutts, Keen et al. 2006). In these studies, a ball rolling down a ramp could be blocked at different points by a barrier. In front of the ramp was a screen, opaque in some experiments, and transparent in others, that contained doors at each possible barrier position. The barrier that was visible on top of the screen indicated which door was the correct one. The result shows that it was difficult for two-year-old children to identify the ball's final resting place. The children's success depended only on the direct cues of actively tracking the ball. They failed to use the barrier cue, probably because it required a choice to be made from indirect and incomplete information. When younger children look for hidden objects, they are affected by where they last saw the object, and not by the proximity of a separate visible landmark. Older children are able to split their attention between a moving object and other visible objects. Younger children often fail to perceive an immobile object standing in the way of the moving object, as moving objects catch young children's attention. Earlier research has focused on young children's inability to represent hidden objects (Piaget 1952). But when an object moves, it is only reasonable to believe that it will keep its course, disintegrate or jump back and forth uncontrollably. When young children seek hidden objects, they are directed by the same reliable information that adults use to track objects.

Working memory

The part of the system in the memory storage area that stores and processes information during a short period of time is called working memory (Baddeley and Hitch 1974). Working memory is primarily represented in the prefrontal cortex (Fuster 1973). Some researchers consider the dorsolateral area to be responsible for the spatial working memory and the ventrolateral area for the non-spatial working memory, but most theorists today indicate that the difference between the dorsolateral and ventrolateral areas has to do with function (Owen 1997). The ventrolateral area handles the maintenance of information and the processing of stored material. The prefrontal cortex is active in tasks that demand executive function (Kane and Engle 2002). Thus, the prefrontal cortex certainly controls attention, solves problems and handles – but perhaps does not maintain – information.

Before six months of age, infants have an appreciable spatial working memory (Schwartz and Reznick 1999; Reznick, Morrow et al. 2004). They recall objects and where they have looked before. For example, they remember an object that has disappeared behind another, as they anticipate the reappearance of that object (Rosander and von Hofsten 2004). Infants

look toward the location where an adult is looking or pointing, and nine-month-olds remember where their mother has previously looked (Butterworth and Jarrett 1991; Carpenter, Nagell et al. 1998; Itakura and Tanaka 1998; Itakura 2001).

When children are to insert an object into an aperture, like in our studies, it is important that they maintain attention up to the moment they release the block; that is, until the goal has been reached. Their working memory must be cleared of all information except that which is relevant to the task (Dempster and Corkill 1999). It is essential that they focus on the task, not deviating their attention or gaze. Ruff and Capozzoli (2003) showed that a child's attention to a specific task increases considerably between two and three and a half years.

Baddley and Hitch (1974) divide the working memory into three parts: visuo-spatial, verbal and episodic. In object-hole studies, the visuo-spatial working memory, which is used for the storage and manipulation of spatial and visual information, would primarily be of use. It can be used to recall sizes and forms, or where an object is and the speed at which it moves in the room. It is also used in tasks that deal with planning and spatial movement. The visuo-spatial working memory is associated with intelligence, perception of time and problem solving.

Inhibition of actions on alternative objects

When a task demands a response that is inhibitive instead of affirmative, more concentration is needed (Gralinsky and Kopp 1993; Gerstadt, Hong et al. 1994; Kochanska, Coy et al. 2001; Durston, Thomas et al. 2002). An inhibitive response makes greater demands on children, because it interferes with the reaction that feels most direct and natural. Inhibition requires that the natural response be interrupted, and this delays the response. The difference between the natural and the self-regulated response is usually called interference (Barkley 1997). There will be an interference when two fighting cognitive processes – an automatic and a controlled one – collide. The classical stroop effect is an example of interference (Stroop 1935). When a word, such as *blue* or *yellow*, is printed in a color that differs from the color expressed by the semantic meaning of the word, there is a delay in the processing of the color of the word. This interference leads to slower reaction times and an increase in mistakes, in both children and adults (Durston, Thomas et al. 2002). Young children's interference decreases with age, which could be related to the development of executive functions (Daniel, Pelotte et al. 2000). When children are going to choose one out of two objects, the child often chooses the most conspicuous over the correct one (Luria 1973; Richards and Holley 1999). If the child is reaching out the

hand towards one of the two items it might be difficult to inhibit. In the clinical field, experiments with inhibition is comparing children with developmental disorders, for example ADHD, with normally developed groups concerning concentration and attention (Quay 1988; Barkley 1990; Schachar, Tannock et al. 1993; Schachar, Tannock et al. 1995; Barkley 1997).

A choice task requires that both alternatives be evaluated. Making a choice includes the control to inhibit alternative choices. Young children have problems with such tasks and tend to make choices too impulsively (Müller, Zelazo et al. 2004; Rennie, Bull et al. 2004). The children might look at the correct alternative but choose the faulty alternative (Mareschal 2000). The performance of the choice task is correlated with the action performed. If the children observe the action they do a choice successfully in a higher degree than when they are going to act themselves. Tomasello (2006) found that two-year-old children performed skillfully in choosing one object of two by pointing. Meyer (1940) reported that children under three years of age failed to fit one of two differently formed objects into an aperture.

General Aims

The predominant goal of these three studies is to explore children's ability to comprehend some of the principles underlying manipulatory actions. Young children's natural attraction to problems relating objects to each other was utilized, such as inserting an object into an aperture, sliding one object over another, and placing one object over another. Very few investigations have used these kinds of fitting tasks in systematic experiments. With this paradigm, we could pose questions that were related to the motor competence as well as the perceptual and cognitive capabilities of the child. In Study I, we wanted to know what the major transitions were in the acquisition of aperture fitting capabilities, by finding out how the children in different ages inserted objects in apertures. Also, we wanted to know if children at the different ages have different strategies when approaching this problem, and to what degree the strategies are predictive and to what degree do they rely on feedback.

The solution of the fitting problem requires three kinds of spatial adjustments. First, the object must be placed over the aperture. Second, the longitudinal axis of the object has to be oriented perpendicular to the aperture in order to insert it. Third, 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 only requires understanding of the first problem. Inserting a cylinder requires the solution of the first two problems; that is, it must be placed over the aperture with its longitudinal axis oriented perpendicular to it. For every other shape, all 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 corresponding aperture than is a rectangular or triangular form because it fits in more ways. The results of Study I suggest that the solution of the fitting problem relies on the ability to mentally rotate the manipulated object into the fitting orientation before the action is carried out.

Studies II and III assessed children's ability to make a choice between objects and apertures in the process of finding a fitting combination. Study II extended the results obtained in Study I by asking how children develop the ability to discriminate object and aperture shapes and how this information is used proactively in the planning of the fitting action. Is it easier or more difficult to choose one out of two items compared to a single item? One

guess could be that with two items, the appropriate relationship between object and aperture can guide you to do it right. To insert a single object into a single aperture, the children must grasp the object in a manner that allows it to be rotated into the correct orientation prior to insertion. When faced with a choice between two items the child has to do an additional step. Before choosing an object, the relationship of each of them to the aperture has to be considered. Thus, this task requires that children represent the orientation of each object in relation to the goal state, and choose the one that will bring about the goal state. In summary, it is more difficult to choose between two objects because both alternatives must be evaluated. Making a choice includes the self-regulation required to inhibit alternative choices. If the child fixates on one of the objects in a two-object task, the tendency to grasp it may be strong even when he/she knows that it is the wrong one. Correspondingly, when children are presented with one object and two apertures, they may not be able to inhibit the tendency to go to the wrong aperture. The results show that making a choice is a much more difficult task than simply making the correct adjustments when carrying out the fitting action.

Study III expanded on the questions about young children's object cognition by systematically comparing tasks requiring relationships between a negative and positive space, between a 3D and a 2D form, and between two 3D objects. In these experiments, both object size and form were manipulated. The results suggest that children's difficulty stems primarily from the task of relating a positive object's 3D form to its negative 2D silhouette.

We continued to ask ourselves whether the tendency to choose the smaller of two objects to be inserted into a large aperture could be explained in terms of a preference for small objects, or whether it reflected the insight that a small object fits into both a small and a large aperture. The study in preparation reveals that the children can relate the size of an object with the size of a hole.

One subsequent goal of the setup depicted above was the difference between girls and boys. There have been repeated claims that boys are more spatially advanced than girls are. In the articles presented in this thesis on the object-aperture problem, no such effects were found. This is not a major point but, because the obtained results disagree with the established view, it deserves to be included in the thesis.

The following questions were assessed:

Study I: What are the major transitions in the acquisition of aperture fitting capabilities? What are the strategies used at different ages? To what degree are the strategies predictive and to what degree do they rely on feedback?

Study II: At what age do young children become able to make an adequate choice between two objects with reference to a single aperture or a

choice between apertures with reference to a single object? How is this ability related to the one of fitting single objects into single apertures? If there is a difference, what is the role played by the increased demands on planning and what is the role of having to make a choice?

Study III: What are the prevailing difficulties involved in solving spatial problems that include a choice between objects and apertures. Are sizes easier to choose between than shapes? What is the role played by the relationships between an object (positive form) and an aperture (negative form), between a 3D and a 2D, and between two 3D forms presented at different orientations?

Study in preparation: At what age can children relate different sized objects to each other?

In addition, earlier studies claim that males have an advantage over females in mental rotation. Nowadays, that has been called in question. Thus, we ask if there are any differences between boys and girls.

Method

Participants

The participants were recruited from birth records. All the subjects of the experiments conducted in Uppsala, Sweden, were recruited in the same way, from Uppsala and its surroundings. Before each study, we sent an invitation letter to parents of children of the ages we were interested in. This letter introduced the purpose and procedure of the experiment. All studies were approved by the ethics committee of Uppsala University. In Study III, Experiment 2 was conducted in Harvard, USA. All parents and children in this experiment were recruited from the greater Boston area.

In Study I, 69 children from four different age groups were studied. The youngest group consisted of eight boys and eight girls with a mean age of 14.0 months ($Sd = 3.4$ days). The second youngest group consisted of eight boys and nine girls with a mean age of 18.0 months ($Sd = 8.2$ days). The second oldest group consisted of nine boys and eight girls with a mean age of 22.0 months ($Sd = 3.6$ days). The oldest group consisted of eleven boys and eight girls with a mean age of 26.1 months ($Sd = 5.2$ days).

In Study II, 55 children from three different age groups were studied. The youngest group consisted of eight boys and nine girls with a mean age of 20.1 months ($Sd = 18.2$ days). The middle group consisted of eight boys and eleven girls with a mean age of 30.2 months ($Sd = 16.0$ days). The oldest

group consisted of eleven boys and eight girls with a mean age of 40.0 months ($Sd = 7.5$ days).

In Study III (Experiment 1), 48 children from three different age groups were studied. The youngest group consisted of eight girls and eight boys with a mean age of 15.1 months ($Sd = 7.0$ days). The middle group consisted of eight girls and eight boys with a mean age of 19.5 months ($Sd = 18.8$ days). The oldest group consisted of eight girls and eight boys with a mean age of 29.4 months ($Sd = 30.7$ days). In Study III (Experiment 2), 36 children from two different age groups were studied. The youngest group consisted of eleven girls and seven boys with a mean age of 21.5 months ($Sd = 1.5$ months). The oldest group consisted of eight girls and ten boys with a mean age of 26.8 months ($Sd = 1.5$ months).

For the study in preparation, eight girls and eight boys with a mean age of 20.0 ($Sd = 16.8$ days) were studied.

Experimental Setup and Stimuli

In all four studies, a set of objects and a box with interchangeable lids were used. The box (14 x 14 x 11.5 cm) was fixed on a table (59.5 x 120 cm), 5 cm from the edge on the side where the child was seated, facing the experimenter (see Figure 1). The objects were presented on a platform behind, but at the same level as, the box with the aperture. In all studies, the children's actions were videotaped for later slow-motion analysis. In Study I, 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. In Studies II and III, one video camera and a video recorder monitored the experiment. In Study I, the videotapes were time-coded with a digital clock giving the time in 1/100 s. In Studies II and III, Score Control v3.3 video analysis software (Soldis, Sweden) was used to score the behavior of the subjects. In Study III (Experiment 2), one VCR camera monitored the experiment.

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

Different lids were attached and locked to the wooden box in the three studies. Each lid had one or two apertures. If there were two apertures, they were of different sizes and/or shapes. When there was one aperture (Studies I and II), it was positioned in the center of the lid. When the lid had two apertures (Studies II and III), they were presented side by side. In Study I seven different shapes, one aperture per lid, were presented to the children: circular (3.5 cm diameter), square (3.6 cm side), equilateral triangular (4 cm sides), rectangular (2.5 x 4 cm), ellipsoid (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), 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) (see Figure 2). In Study II, nine different lids with six different shapes were presented to the children (see Figure 3). Six of the lids each had one of the following apertures: circular, square, rectangular, ellipsoid, isosceles and right-angled triangular (see measurements in Study I). Three lids each had a pair of the above-mentioned shapes: circular together with square, rectangular together with ellipsoid and isosceles triangular together with right-angled triangular. When the apertures were elongated, they were presented with the short side in the fronto-parallel plane. In Study III (Experiment 1), four lids each had one of the following apertures: circular (3.5 cm and 6.0 cm diameter), and square (3.6 cm and 6.0 cm sides) (see Figure 4).

Figure 2. Displays for the hole-fitting task of Study I.

Figure 3. Displays for the hole-fitting task of Study II.

Figure 4. Displays for the hole-fitting task of Study III, Experiment 1.

The wooden objects were 1 mm smaller than the apertures in all dimensions, fitting snugly into the corresponding apertures. The cross-sections of all objects had approximately the same circumference. In Studies I and II, the blocks included in the studies measured 7 cm in length, the short side varying between 10.5 cm and 13 cm in circumference. The different objects had different numbers of insertion possibilities. As long as the longitudinal axis of the cylinder was vertical, it fit in every possible orientation. The square fit the aperture in four ways in each of the vertical orientations. The equilateral triangle fit the aperture in three ways in each of the vertical orientations. The rectangular and the ellipsoid shapes fit the aperture in two ways in each of the vertical orientations. The isosceles triangle fit in one way in each of the two vertical orientations. The right-angled triangle only fit the aperture in only one way. In Study III (Experiment 1), balls and the cubes in two different sizes were presented. The balls fit in every possible orientation. The squares fit in four ways in each of the six vertical orientations. When the objects were presented in pairs (Studies II and III, Experiment 1), the colors were identical (see Figures 3 and 4).

The main difference with Study III (Experiment 2) was that the objects were visible throughout the experiment. Like in the Studies II and III (Experiment 1), the child was to choose a 3D and insert it into an aperture, whereas in the aperture condition (Experiment 2), a tall object was to be placed in one of two short 3D boxes. The appropriate object thus remained half visible when the task was finished. The tower condition (Experiment 2) similar to that of the study in preparation, involved placing one 3D object on top of another object of the same shape so as to form a "tower". In contrast to Experiment 2, the movable object and the two candidate base objects were all closed and solid. Thus when the object was placed on a base object it remained visible. In the form condition (Experiment 2), a 3D object was to be placed on top of a 2D form of the shape of the object's silhouette and again remained visible.

There were five different types of blocks whose target surfaces were in the shape of a small equilateral triangle block (3.25 cm sides, for training only), a small and large circle (2.75 and 5.5 cm diameter), and a small and large square (2.5 and 5 cm sides) (see Figure 5). All blocks were cylindrical in shape and were either 7.5 cm tall (aperture condition) or 3.25 cm tall (other conditions). In the aperture condition, the blocks could be fit into apertures embedded in 10 x 10 cm wooden bases. Each aperture was approximately 3.75 cm deep, with an aperture slightly larger than the critical surface of the block that matched it (small triangle: 4 cm; small and large circles: 3 and 6 cm, respectively; small and large squares: 2.75 and 5.25 cm, respectively). In the tower condition, the blocks were to be placed on tower bases consisting of blocks of the same sizes and shapes as the target blocks. In the form condition, the blocks were to be placed on separate 10 x 10 cm

pieces of laminated paper presenting solid forms of the same sizes and shapes as the critical surfaces of the target blocks at their centers. In all conditions, a training block was painted orange while the test blocks were red, blue, yellow and green. Moreover, the critical surfaces on which the child could place an object on the three types of bases were painted pink. These pink forms were therefore the same in the aperture, tower and form conditions.

In the study in preparation, we used two differently sized cubes (3.6 cm and 6.0 cm side), the same as in Study III, Experiment 1, each fixed on cardboard, and two movable cubic boxes with covered tops and open bottoms that served as covers for the objects (see Figure 6). The open space inside the larger cover was a 6.1 cm cube; the space inside the smaller cover was a 3.7 cm cube. The outer side measures were 6.5 and 4.1 cm, respectively. The cubes were of four different colors (red, blue, yellow and green), and the covers were grey. The combinations of the colored objects were randomly determined for each experiment.

a

b

c

Figure 5. Displays for the (a) hole-fitting, (b) tower-building, and (c) form-fitting tasks of Experiment 2.

Figure 6. Displays for the cover-fitting task of the study in preparation.

Procedure

After getting acquainted with the families and explaining the purpose of the study, the experimenter invited the parent to sit in a chair with the child in his/her lap. The chair was vertically adjustable so that it would be possible for the child to have a complete view of the setup. Before the experiment started, the child was given a few demonstration objects to manipulate and insert into the apertures to make sure that he/she understood the task. The demonstration objects were different from the objects in the experiment and fit into the apertures without any orientation constraints. The parent could encourage the child to insert the objects into the apertures, but was asked to avoid assisting them during the trials.

The objects were presented on a platform at the far side of the box, one trial at a time. The order between the stimuli was randomized. In Study I, 28 trials were presented to the children. Half of the objects were presented in a standing position, half in a lying position. The objects were presented twice in both positions. When lying down, the longitudinal axis was oriented away from the subject, and the shortest axis of the cross-section was the horizontal one. The exception to this rule was the ellipsoid object, which could only be presented with the longest axis of the cross-section oriented horizontally. The duration of the whole experiment was varied, 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 and if the child was easily distracted and unfocused it could take as long as one hour, including pauses.

In Study II, 24 trials were presented to the children. The pair of objects or apertures was presented both on the left and right sides of the child. All objects were presented in an upright position. The blocks with elongated cross-sections, i.e. the ellipsoid, rectangular and triangular forms, were presented with the longest cross-section oriented in the child's fronto-parallel plane. Thus, those objects had to be turned 90° around their vertical axis to fit the aperture. This was done to force the subjects to reorient these objects before fitting them into the aperture. Moreover, the right-angled triangle, with only one insertion possibility, was always placed with the correct side up, in both Studies I and II. In the one-object/two-aperture conditions, six object-aperture combinations were included. The cylinder and the square blocks were presented with cylinder/square apertures, the rectangular and ellipsoid blocks were presented with the ellipsoid/rectangular apertures, and the triangular blocks were presented with the triangular apertures. In the two-object/one-aperture condition, six object-aperture combinations were presented. The cylinder and square apertures were combined with both of their corresponding objects, the ellipsoid and

rectangle apertures with both of theirs, and the two triangular blocks with both of theirs. The duration of the whole experiment was variable, but most of the children finished the session within 20 minutes (range: 12–60 minutes). In Study III, Experiment 1, 24 trials were presented to the children. The objects were presented twice in a rotated (i.e., opposite) order. The orientation of the cube's cross-section was the same as that of the aperture. The duration of the experiment took approximately 20 minutes (range: 12–45 minutes).

The last part of Study III was carried out at Harvard University. In Experiment 2, 18 to 30-month-old children were presented with three conditions: aperture, tower and form. The aperture condition began with a training phase during which the experimenter demonstrated inserting the orange triangular block into a wooden base with the triangular aperture, noting how she had “covered the pink spot and made it fit.” The experimenter then encouraged the child to do the same. In each of the test trials, the experimenter showed the child two wooden bases (tipping them forward to ensure the child had seen their two apertures with the pink bottoms) and then placed them side by side on the table and encouraged the child to “cover the pink spot and make it fit.” Following this, the child was presented with the target block on the table between him/her and the bases. When the child gave a correct response, the experimenter commended him/her. When the child gave an incorrect response, the experimenter moved the block to the correct aperture and noted how she had “covered the pink spot and made it fit.”

The tower and form conditions each began with a training phase during which the experimenter demonstrated placing the orange triangular block onto the appropriate tower base or form, noting again how she had “covered the pink spot and made it fit.” After the child repeated this action, the experimenter proceeded to the test trials by showing the child the first pair of test tower or paper bases (tipping them forward to ensure the child had seen their pink top surfaces) and then placed the bases or forms side by side on the table. The trials proceeded thereafter as in the aperture condition, with the same instruction to “cover the pink spot and make it fit.”

To render the three tasks of Experiment 2 in Study III as comparable as possible, target object shapes were chosen such that the visible portion of the object at the end of the action was the same for all three tasks. Moreover, the choice demands were equated: in each trial, the child chose between two bases on which to place an object. Both to maximize the similarity of instructions across tasks and to encourage children to choose the correctly shaped base, the surfaces on which an object could be placed in each task were painted bright pink, and children were told to place the object on the base where it would cover this pink surface completely. Thus, the children were discouraged from placing a small object onto a large base.

The aperture, tower and form conditions were highly similar: all were initiated with the same instruction, involved visible objects and placed the same demands on the child's action planning. Nevertheless, these tasks required different representations of the spatial relationship of the target object to its surroundings. The aperture condition, as in Experiment 1, required that children relate the shape of a 3D object to that of its target 2D surface and also relate the positive shape of that surface to the negative shape of the aperture in the base object. The form condition differed only in the second requirement, in which the children had to relate the shape of the object's target surface to the positive shape of the form on the base surface. The tower condition differed in both requirements, with the children relating the shape of the object to that of a second 3D object, the base of the tower. By comparing these tasks systematically, we attempt to distinguish between the effects of these different demands on children's object representations.

In the study in preparation, eight trials were presented to the children. The objects were presented twice in an identical order, twice in rotated order. The differently sized cube covers were placed side by side on the platform in front of the child at the far side of the box. The position of the two objects was rotated between the trials and the two trial combinations were presented four times. The experiment was introduced to the subjects by presenting one object in the center of the display and two covers in front of the object, side by side. The child was encouraged to take one of the two covers and place it over the object snugly. The procedure was then repeated with the other object. After warm-up trials with a much smaller object, children were given eight test trials, half with the large cube and half with the small one. In half the trials with each object, the large box appeared on the left; the order of the trials was randomized separately for each child. In each trial the experimenter first pointed to the cube to be covered, then drew the child's attention to the differently sized boxes, saying: "under which cover should the block be hidden?" and waited while the child chose a box and attempted to cover the cube. The experiment lasted approximately five minutes.

Data Analysis

Study I emphasized the orientation of the object, and Studies II, III, and the study in preparation, the correctness of the decision. Only the first attempt was counted.

Appropriate pre-adjustments of object position: In Study I, the measures concentrated on the orientation of the objects. Each trial was judged at the instant the object touched the aperture. Both horizontal and

vertical adjustments were evaluated. A perfect outcome was when the object was vertically upright and the cross-sections of the object and the aperture matched. The positional orientation was considered appropriate if the object was placed over the hole. The orientation was considered vertically appropriate if the longitudinal axis was deviating less than 30° from verticality. If the vertical orientation inclined more than 30°, it was not meaningful to proceed with judging the horizontal alignment. Thus the error was coded as a vertical error. The horizontal orientation was considered appropriate if the cross-section was less than 30° from the orientation of the aperture. If the object orientation was turned more than 30° from the aperture orientation, the error was coded as a horizontal error (see Figure 7).

Reliability: As the 30° deviation cutoff was arbitrarily chosen, the pre-adjustments were judged by a second coder (Study I). Cohen's Kappa was used to evaluate the inter-rater reliability for both the vertical and horizontal dimensions. In Study I, the two coders disagreed on 31 of 302 cases. Only the results of the primary coder were used in the analysis of the results. Cohen's Kappa was satisfactory for both the horizontal pre-adjustments ($r = 0.87$), and the vertical ones ($r = 0.80$). In Study III, Experiment 1, four girls and four boys from each age group were coded by a second coder. The two coders agreed on 100% of the trials. In the study in preparation, eight subjects (four girls and four boys) were coded by a second coder. The two coders agreed on 100%. Thus, the reliability of their coding was found to be 1.0 for the appropriate choice measure and 1.0 for the correct choice measure.

Laterality: In order to analyze handedness in Study I, the hand used for each trial was coded.

Correct decision: In Studies II, III and the study in preparation the measure was focused on the choice, which was coded as correct or incorrect when the object touched the aperture. In the study in preparation, a choice was coded when the child grasped one of the covers and moved it to the cube. If an object or a cover was grasped but the child either did not move it toward the object or began to move it but interrupted this act before arriving at the object, no choice was coded. When the child had chosen an appropriate box and attempted but failed to cover the object, the experimenter assisted the child in completing the task to avoid frustration. Each choice was coded for its appropriateness and correctness. Because the small object could fit into the large aperture in Study III, Experiment 1, all objects could be inserted except the large object with a different form, and under these conditions the probability of choosing correctly by chance was 83%. When the aperture was small, only the object that matched it could be inserted and the chance probability was thus 50%. The chance of making an *appropriate* choice was therefore 67%. As the large box could cover both objects in the study in preparation, choice of that box was always appropriate in Study III, Experiment 1, and the study in preparation. Chance

performance was therefore 75% for appropriate choice. In all the choice experiments, the chance probability of making a *correct* choice was 50%.

Successful insertion: In Studies I and II, the attempts to insert the object into the aperture were coded as successful or unsuccessful.

Time: All four studies measured the duration from grasping the object until touching the lid of the aperture box. Studies I and II measured the duration until the object was either inserted into the aperture or the subject gave up or, for Study II, made another choice.

Statistical analyses: To analyze the data, a general linear model Repeated Measurements ANOVA and posthoc tests with Pairwise Comparisons were used. All posthoc tests were Bonferroni corrected.

Figure 7. The coding of the positional, vertical, and horizontal pre-adjustments.

Object Orientation (Study I)

Results

A box with different apertures and objects to match was presented to the children. The objects were presented both standing and lying. In this study the following questions were assessed: What are the major transitions in the acquisition of aperture fitting capabilities? What are the strategies used at different ages? To what degree are the strategies predictive and to what degree do they rely on feedback?

Successful Insertions and Appropriate Pre-Adjustments

The task of inserting objects into apertures proved to be very attractive and the subjects completed 86% of the trials. There was a significant difference between the two youngest and the two oldest groups in inserting the object. Fourteen-month-olds succeeded in inserting the object in only 20% of the trials, 18-month-olds in 33%, 22-month-olds in 78%, and 26-month-olds in 81%. If the children pre-adjusted the orientation of the object before arriving at the aperture, they were often able to insert the object into the box, and when they reached the aperture with an inappropriate orientation of the object, they failed to insert it in most cases. While the two youngest age groups did not typically pre-adjust the orientation of the object, the two oldest age groups turned the object appropriately most of the time before arriving at the aperture. There was a significant effect of Object Form; that is, the more insertion possibilities that were available, the more successful the infants were. The children were significantly more successful with objects that were standing up than with those that were lying down. When the object reaches the aperture, the presentation mode should not affect the possibility to insert it. Quite correctly, the difference between standing and lying is not significant for the two oldest ages, when excluding the right-angled triangle from the group with the 22-month-olds.

Duration

The 22-month-olds spent more time trying to insert the objects than did the younger children. However, the 22-month-olds also succeeded significantly more than the 18-month-olds did. The 26-month-olds went on manipulating for a shorter amount of time, but had a significantly higher percent of insertions than did the 22-month-olds. The result shows no sex differences, either for success or duration.

Laterality

Study I shows that the children were rather consistent in their choice of hand. The right hand was used in the greater part of the trials, the overall proportion of reaches made with this hand being 80%. Eight of the 69 children used their left hand more often than their right, but none of them used the left hand exclusively. Nine children used their right hand in all trials exclusively, and four additional children used their right or both hands in the trials.

Discussion

The most essential finding in this study was the considerable difference between the 18- and 22-month-old children concerning insertion ability, and it has to do with action planning. From 18 to 22 months, there is a transition in the acquisition of aperture fitting capabilities, i.e. from feedback to pre-adjustments. Successful insertion was associated with appropriate pre-adjustments before arriving with the object at the aperture. The two oldest groups pre-adjusted, the two youngest did not; instead, they used a feedback strategy. If the strategy was predictive, it would not make a difference how the objects were presented. The 26- and 22-month-olds pre-adjusted the object orientation in an appropriate way both vertically and horizontally before arriving at the aperture, but at all ages the infants were significantly more successful with objects that were standing up than with those that were lying down. However, the successful insertions for the standing objects compared to the lying ones are not different for either the 26-month-olds or the 22-month-olds if the right-angled triangle is excluded. This strengthens the conclusion that the children in the two oldest age groups are able to pre-adjust the orientation of the object before arriving with it at the box. Piaget

and Inhelder (1956) claimed that still until about two year of age, children are not fully aware of how to relate object to each other, but act more on intuition. Our result indicate that children begin to have a clear picture of the relationship between objects at a somewhat earlier age, since they raise the objects and rotate them appropriately ahead of time from about 22 months of age. The youngest age groups relied on feedback and did not seem to truly examine the object before approaching the aperture. A child needs to have an idea of how to reorient an object before adjustments can be made. Such an idea can only arise if he/she can imagine the goal state and mentally rotate the manipulated object into the fitting position before the action is carried out. The result shows how these pre-adjustments become more sophisticated with age. Even if the 22-month-olds did pre-adjust, the 26-month-olds succeeded to a greater extent (the 22-month-olds succeeded in 46.1% of the cases while the 26-month-olds succeeded in 68.8%), at the same time as they reached the aperture and inserted the object significantly more quickly and smoothly than the 22-month-olds did.

An object with more insertion possibilities is not only easier to handle and insert but is also most likely easy to understand. This reasoning can be compared to the studies of mental recognition that state that the more mental steps you have to go through, the more time is needed to decide whether two objects are identical (Shepard and Metzler 1971; Shepard and Feng 1972). It takes a certain amount of time to recognize an object. An object with more orientation possibilities does not need to be rotated to the fitting aperture as much as an object with fewer orientation possibilities does.

The 14-month-old infants made fewer pre-adjustments than the older infants did, and their manipulations were more exploratory than functional. They had a higher tendency to turn or rotate the objects, move them from one hand to the other, move them to their mouth or move them closer to look at them before transporting them to the lid. The goal, i.e. to insert the object into the box, seemed clear to the 14-month-olds, since they had no problem inserting the less difficult pre-experimental objects. But the fact that they did not systematically pick up the objects that were lying down and, in about a quarter of the cases, lay down the ones that were standing up, is an example of how little they understood about how to orient the objects in order to insert them into the aperture.

At 18 months, children turned up some of the horizontally placed objects but not others. The ones that were turned up more seldom had an asymmetrical cross-section and were presented with the broadest dimension oriented vertically. The results indicate that it was not the asymmetry of the cross-section itself but the presentation of the object that made the children inclined to place them horizontally on the lid. The result indicates that the children did understand the goal but were unrealistic about how to fully implement it, something Meyer (1940) called partially planned strategy.

Infants under one year are able to compare simple 3D object with 2D pictures (Rose, Gottfried et al. 1983; Skouteris, McKenzie et al. 1992; Younger and Johnson 2006). To recognize an object, its spatial characteristics must be known, and its different parts must be remembered (Skouteris, McKenzie et al. 1992). The children younger than 22 months did not succeed when the blocks were presented lying down. Most likely, this has to do with the fact that it is not the whole 3D object that is represented by the aperture, but just one of its cross-sections. The children see the object from above showing its short side, they might relate it to the aperture that shows a matching silhouette from the viewpoint parallel to the object's major axis (Rock 1974; Tarr and Bülthoff 1995; Tarr and Bülthoff 1998). If the object is lying down, the children get quite a different picture than the opening of the aperture, and will most likely produce a worse result.

The 22-month-olds succeeded more, and spent more time trying to insert the objects than did the younger children. To initiate and maintain an action, the child must be motivated and have an interest in the task. That counts for relating objects to each other as well as learning to walk. When children learn to walk, they continue trying even if they fail again and again. It is as if they knew that they soon will be mastering this skill (Adolph, Vereijken et al. 2003; Garcíaguirre and Adolph 2006; Joh and Adolph 2006). It only seems natural that if you normally accomplish a task well, the occasional failure will make you more persistent since you are used to succeeding. The 26-month-olds went on manipulating for a shorter amount of time, but had a significantly higher percent of insertions than did the 22-month-olds.

Handedness reflects a greater capacity for one side of the brain in reference to certain tasks (Berk 2006). For right-handed people, hand control is better developed in the left hemisphere, whereas the right hemisphere is dominant for left-handers. Almost 90% of the population is right-handed (Bayley 1969; Corballis 1991; Hepper, Shahidullah et al. 1991; Corballis 1997). That is in agreement with the results of Study I, which show that 80% of the children predominantly used the right hand.

Some researchers assert that lateralization occurs slowly throughout childhood (Lenneberg 1967), others that children are born already lateralized (Grattan, De Vos et al. 1992; Rönnqvist and Hopkins 1998). Even if it emerges earlier, hand preference is difficult to detect before eight months. By the end of their first year, infants typically show a hand preference for manipulating objects (Hinojosa, Sheu et al. 2003). After 18 months, hand preference become more stable, but it is not reliable until age four (Needlman 2002). Rönnqvist and Domellöf (2006) proposed that human hand preference originates in arm advantage, as it is not until the age of two to three years that the muscles that represent fine precision and accuracy in the hand are fully developed. Although a majority of the parents in Study I showed ignorance of their child's handedness, the results of that study show that the children were rather consistent in their choice of hand. The reason

parents were uncertain of their children's handedness is probably because it fluctuates with the difficulty of the task. Activities that are more hand-specific are those that require either a great deal of practice and fine detail (e.g., inserting an object into an aperture) or the coordination of large muscle groups for a sudden, smooth action (e.g., throwing a ball). The fact that these sorts of activities take up a great deal of effort provides a clue to the relationship between handedness and the brain. When the task is easy, there is a greater probability that either hand will be used (Fagard and Marks 2000). When it is a new or complex task like 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 handedness does not fluctuate as much in non-crawlers as in crawlers. In a study of different grasping techniques, Fagard and Lockman (2005) found that when grasping involved bimanual manipulation, handedness was more apparent than it was in simple grasping. Postural development also explains changes in one versus two-handed reaching strategies, facilitating simple versus bimanual reaching in different ages.

Shape Discrimination and Choice (Study II)

Results

In this box study, the children were presented either to one object that was going to be fitted in one of two different apertures, or two different objects where one was going to be matched to an aperture. The following questions were assessed: At what age do young children become able to make an adequate choice between two objects with reference to a single aperture or a choice between apertures with reference to a single object? How is this ability related to the one of fitting single objects into single apertures? If there is a difference, what is the role played by the increased demands on planning and what is the role of having to make a choice?

Correct Decision

The subjects completed 95% of the trials. Twenty-month-olds chose both the pair of objects and the apertures randomly. Even 40-month-olds did not succeed with the most difficult choice. However, the children improved with age in making the correct choice; that is, the 40-month-olds chose more correct combinations than did the 30-month-olds, who in turn chose more correct combinations than the 20-month-olds did. It was more difficult to choose between two objects than between two apertures. The 30- and 40-month-olds showed a result above random on the cylinder/square and ellipsoid/rectangle problems. However, they never succeeded significantly with the triangular problem.

Successful Insertion

When the decisions were correct, the children in the two oldest ages succeeded well in inserting the objects into the aperture – even the most difficult objects, i.e. the triangular shapes. The 20-month-olds succeeded well with the easier cylinder and the square forms. Overall, the 40-month-

olds succeeded in inserting the objects into the apertures in 93% of the attempts, the 30-month-olds in 81%, and the 20-month-olds in 46%. Success depended on how many possibilities there were for inserting the object. The time the children continued to try with an incorrectly chosen object, i.e. persistence time, depended on object form. When the 30- and 40-month-old children failed to insert the objects, they rapidly switched to the other block or tried the other aperture. This was the case for all objects except the triangles. It was the other way around with the 20-month-olds, who were busy with the triangles the shortest time and with the cylinder/square the longest time.

Duration Measures

The time it took to successfully insert an object after a correct choice had been made showed a main effect of the form of the object. The more insertion possibilities that were available, the less time it took to insert the object. The 20-month-olds needed more time to insert the objects than the older children did. The 30- and 40-month-olds used similar durations for getting the object through the aperture for all forms except the triangular ones, for which the duration was longer. Although girls and boys did equally well, the boys were significantly faster in solving the problems.

Discussion

It was easier for the children to choose between the pair of apertures than the pair of objects. When choosing between the pair of apertures, the children could decide the direction of the object during the approach itself. When a choice was to be made between the pair of objects, the children had to be clear about the appropriate relationship with the aperture already when grasping the chosen object. But the difference between these conditions was not very great. Instead of comparing the object with the two apertures at a closer distance in a more mature manner, the children transported the object equally quickly in the two conditions. Earlier research has found that younger children act more on impuls (Gauvain and Rogoff 1989), rather than gathering enough information to find the optimal solution (Vurpillot 1968).

The choice itself was of greater importance than the kind of choice made. Compared to Study I, wherein 22-month-olds succeeded in fitting a single object into a single aperture, it was somewhat surprising that the 20- and 30-month-old children had such difficulties in Study II. It was the choice

that was most difficult, because if only the success in inserting the correctly chosen object is considered, the children in Study II performed as well as those in Study I. Naturally we expected a result that was slightly poorer for a choice task than for a single object-fitting task. But the aptitude to choose requires more than mental rotation, the ability to imagine goal states and the understanding of means-end relationships. It also demands evaluation of the alternatives, and young children are not very good at this (Vurpillot 1968). As already mentioned, they tend to make decisions without complete information. We can draw a parallel to the ramp studies conducted by Keen and colleagues (Claxton, Keen et al. 2003; Keen 2005; Kloos and Keen 2005; Kloos, Haddad et al. 2006; Shutts, Keen et al. 2006). Two-year-old children were unable to identify a ball's hiding place by means of indirect cues. From this, it seems that it is both the impulsivity of the young children and their lack of information that make them choose an incorrect aperture in Study II.

Making a choice is also a question of inhibiting the alternative choices (Rennie, Bull et al. 2004). Several studies report that children have difficulties in inhibiting a response and tend to make choices too impulsively (Munakata 1998; Mareschal 2000; Durston, Thomas et al. 2002; Müller, Zelazo et al. 2004; Rennie, Bull et al. 2004). It has even been reported that in a choice situation children might look at the correct alternative but choose the other, incorrect, alternative (Mareschal 2000). The present study indicates that even the oldest infants were not totally self-regulating in the context of the present problem. Even when the children should have known the correct answer, their ability to choose the correct object was still poor. Certainly, this is partly due to failure of inhibition control. This result tells us that executive functioning, in which inhibition is a vital factor, is not yet developed by 20 months, and is only just so by 30 months.

As we saw in Study I, the larger the number of object orientations that fit the aperture, the greater the tendency was to solve the problem. The 40-month-olds could correctly evaluate the differences in cylinder/square in over 90% of the cases, while they still chose the triangular alternatives randomly. The present results suggest that children do not represent shapes as templates, but rather form schemas on the basis on feature analysis of the visual forms (Clements and Battista 1992; Clements, Swaminathan et al. 1999). As the schemas are developing, children begin to define shapes from their appearance (van Hiele 1986; Clements and Battista 1992).

Size and form (Study III)

Results

The following questions were assessed: what are the prevailing difficulties involved in solving spatial problems that include a choice between objects and apertures? Are sizes easier to choose between than shapes? What is the role played by the relationships between an object (positive form) and an aperture (negative form), between a 3D and a 2D form, and between two 3D forms presented at different orientations? Two experiments were conducted to answer these questions. In Experiment 1, the children were encouraged to choose between objects of different form and size. In the Experiment 2, the children were presented to a hole task, a tower task, and a form task. The hole tasks was similar to the Experiment 1 with one difference. In Experiment 1, the object disappeared completely while in Experiment 2, the object was still visible once it had reached the goal. In the tower task, one of two 3D objects was to be placed over another 3D object. In the form task, one of two 3D objects was to be placed over a 2D silhouette. We asked ourselves what children would find most difficult when solving these tasks.

Correct match

The subjects completed 96% of the tasks. Overall the 30-month-olds in Study III, Experiment 1, had a significantly better result than did the 15- and 20-month-olds, who performed near random. When the sizes were equal the 30-month-olds, but not the 15- or 20-month-olds, showed a result that was above chance. When the aperture was small and the objects of different sizes, the 20- and 30-month-olds chose the small object more frequently than by chance but the 15-month-olds chose the objects at random. When the aperture was large and the objects were of different sizes, the 15- and 20-month-old children chose the small object more often than random. The results show a strong bias for choosing the small object over the large one and for choosing the ball over the cube. This means that the children did not match the object with the aperture.

In the aperture condition (Experiment 2), older children chose the correct match in shape but only a non-significant tendency in size. Younger children's choices were random in both size and shape trials. In the tower condition, older children succeeded in choosing the correct match in both size and shape. The younger children showed a marginal tendency to match sizes but not shapes. In the form condition, older children chose to place the object on the form of the correct size and shape, but the younger children picked the correct match on both size and shape at random. Comparing performance across 3 (Task: aperture vs. tower vs. form) by 2 (Age: younger vs. older children) by 2 (Condition: size vs. shape), there were significant effects among Task and Age, but not between any other main effects and interactions among the variables. Comparing performance across 2 (Task) by 2 (Age) by 2 (Condition), there were significant effects among Task and Age, and no other effects.

Discussion

Early in life, infants realize that a distant object has a smaller retinal size than a nearby object does. Importantly, though, they seem not to know how much smaller it is. Even though four-month-old infants can compare the width of a ball to that of an opening and judge whether the ball can fit through the opening (Spelke, Breinlinger et al. 1992) when they are at the same distance, the relationship between objects and aperture, at least when they are presented at different distances, is not clear to them. When children were presented with two objects and a single aperture through which only one object could pass, older children chose the object of the correct size and shape, whereas younger children selected objects irrespective of their relation to the aperture. When children must choose one of two differently sized objects that are to be fit into an aperture, they might choose a larger object to fit into the smaller aperture, only because the object that is further away looks smaller than it really is. The result reveals that this was not the case. On the contrary, the younger children showed a baseline preference in the size task, and chose the smaller object systematically. They might understand the size relations between the object and the aperture, and realize that the smaller object will fit more easily than the larger object into apertures of *both* sizes. In Experiment I, 15- and 20-month-olds also showed a preference in the form condition; i.e. the ball was chosen over the cube. Irrespective of its relation to the aperture, the ball might be chosen simply because it can be rotated in any way, it is easier to grasp, it displays greater symmetries, or due to some other reason than spatial demands. 15 months did not succeed either on sizes or shapes. Though the 20-month-olds did

relate the small objects to the small apertures, they also matched the small objects with the large apertures. Even if there are indications that the children manage the sizes before the shapes, the experiment does not answer the question whether it is easier to choose between different sized objects than between objects of different shapes. This question was, however, answered in the study in preparation.

Like in Studies I and II, the different ages approached the problem in different ways. When the children had inserted the object, the 30-month-olds were satisfied most of the time, while the two youngest age groups attempted with the other incorrect one. We already know that up to a certain age children have difficulty inhibiting a response (Munakata 1998; Mareschal 2000; Durston, Thomas et al. 2002; Müller, Zelazo et al. 2004; Rennie, Bull et al. 2004), and that they might choose the incorrect alternative on purpose (Mareschal 2000); it may be due to failure of response control. The present study indicates that even the oldest infants were not totally self-regulating in the context of the present problem. The result of this study tells us that executive functioning, in which inhibition is a vital factor, is not yet developed in the younger children, and is only just developed in the older ones. Even when the children should have known the correct answer, their ability to choose the correct object was still poor. It might also be that the children simply find it fun to explore the relationships of objects. They may well be able to inhibit themselves, but they might be so motivated that they intentionally continue their exploration.

The findings of Experiment 2 confirm and extend the principal findings of Experiment 1. First, although the children were tested under conditions that evoked no competing baseline preferences, younger children failed to choose the appropriate object, in not only shape but also size. The issue is probably not one of insufficient motivation or distraction, because they seemed engaged in the task and attentive to the objects, and while they failed in some experiments they succeeded in others. Second, older children succeeded in the aperture-fitting task, not only when the objects had the simplest and most symmetrical shapes but also when the shapes were more complex. Together, these findings suggest that by the beginning of their third year, children master the fitting problem.

One of the questions asked was if there is any difference between sizes or shapes, and, if so, what is it due to? Although older children performed equally well on size and shape whereas younger children failed on both, the younger children performed much better in size than in shape trials. In shape trials, the bases of the two objects are globally similar; to assess which base fits the object, one must compare their surfaces in some detail. One has to rotate the object mentally. In size trials, in contrast, a global comparison of the base objects suffices to indicate which base fits the moveable object. Young children's uniquely high performance in size trials therefore suggests that they approach these tasks by assessing the global

properties of the 3D objects, not by analyzing the shapes or arrangements of the objects' 2D surfaces.

Another of the questions asked was what do children find most difficult when relating a 3D object to a 2D silhouette. The result says that it is unimportant for the children's performance if the objects are visible or not. Even though the objects remained visible throughout the hole-fitting task, the children performed as poorly as did those in Experiment 1, in which the objects could not be seen at the end. Experiment 2 provided no evidence that the children's difficulty stemmed from the need to relate the shape of a 3D object to that of a 2D surface. As children performed as well in the form task (which required a 3D-2D relationship) as in the tower task (which did not), we see that mental transformations do not limit children's performance. From Study I, however, we have learned that when children must not only select the correct hole but also actively propel an object through it, difficulties with mental rotation may emerge. The critical difference between the three tasks in Experiment 2 was that the base shape delimited a negative space in the hole-fitting task and a positive space in the tower and form-fitting tasks. Besides, we have seen that it is easier to work with familiar objects presented in the same way than with objects that look different (Rudge and Warrington 1991; Skouteris, McKenzie et al. 1992; Tarr and Bülthoff 1995; Tarr and Bülthoff 1998). While in the tower condition the two objects were copies of one another, the other tasks had objects that required a rendering of a 3D object to a 2D display. As children made significantly more errors in the hole task than in the others, we conclude that part of the difficulty of the hole task stems from the requirement that the shapes of positive and negative spaces be matched.

Positive and negative space (Study in preparation)

Introductory remarks

Several findings from Study III shed light on the sources of young children's difficulty in aperture-fitting tasks. These tasks involved the same objects and very similar gestures of placing an object on top of another visual display, but the critical difference between them is that the base shape delimited a negative space in the aperture task and a positive space in the tower and form-fitting tasks. Children's superior performance in the tower and form tasks, relative to the aperture task, therefore provides evidence that part of the difficulty with hole-fitting tasks stems from the requirement that the shapes of positive and negative spaces be matched. When it comes to understanding size relations, the results of Study III are not as clear. The strong bias for selecting the small objects in Experiment 1 and the random tendency to select the large and the small holes in Experiment 2 might have a rational reason. In Experiment 1, the children may have understood the size relations between the object and the aperture, and realized that the smaller object would fit more easily than the larger object into apertures of *both* sizes. Thus, when presented with a large and a small object paired with a small aperture, they chose the small object in 78% of the trials. In these trials, the large object simply would not fit the small aperture. When presented with a large and a small object paired with a large aperture, they also chose the small object in a majority of the trials (80%). In these trials the small object fit the small aperture as well as the large one. Thus, all choices were appropriate. In Experiment 2, the objects to be fit into the hole were always small while the holes were large and small. Thus the object always fit into both holes. In conclusion, from this experiment we do not know whether the children chose the small object because it always fit the aperture or whether they simply had a preference for small objects. Therefore, the subjects' tendency to choose the small and the large aperture equally often does not necessarily reflect an inability to understand size relations.

In the study in preparation, we evaluated the children's size concept in a different way. In each trial, they were shown one solid cube and two open

cubic boxes presented with their open face down. We made sure that the children realized that the boxes were opaque. One box fit over the object tightly, and the other was larger or smaller than the object. When the object was large, only the large box could cover it, but when the object was small both the large and small boxes covered it. Thus, in all conditions, the large box could always cover the object presented. A general preference for choosing a small object that could have explained the results of Study III (Experiment 1) would not be logical in this experiment. On the contrary, choosing the small cover when the object to be covered was large would lead to a misfit. To fit the covering box over the object, the child should either always choose the large or the matching box. As the preference for small objects in Study III (Experiment 1) was greatest for the 20-month-olds, only a group of that age was studied in the study in preparation. Hence, we asked ourselves if children can relate sizes earlier than forms.

Results

All the children completed the experiment. In 79.7% of the trials, they chose a box that covered the object (chance = 75%, $t = 0.97$; $p = .350$). Across all the trials, they chose the large cover in 46% of the trials and the small cover in 54% of the trials, exhibiting no significant preference for the smaller cover (paired $t(15) = .426$; $p = .676$). The choice of cover was, however, significantly related to Object Size ($F(1, 14) = 8.758$; $p = 0.01$, $\eta^2 = 0.39$). When the object to be covered was small, the infants chose the small cover in 67% of the trials and when the object to be covered was large, they chose the large cover in 59% of the trials. The tendency to choose a small cover when a small object was presented was not significantly greater than the tendency to choose a large cover when a large object was presented ($F < 1.0$).

Discussion

The question asked was at what age children can relate sizes to each other. The result shows that the children can choose between sizes when they are 20 months, apparently earlier than they can choose between forms. The children did not have a consistent preference for the smaller object in this situation. This suggests that the reason the 20-month-old children in Study III (Experiment 1) chose the smaller of the objects in a majority of cases was not primarily because they had a general preference for small objects, but

because the small object always fit the hole. Indeed, their choice of cover size was significantly related to the size of the object to be covered. The children in this experiment represented the size relations between the objects and covers and used these relations to guide their choice of an appropriate cover for an object. Compared to the previous studies, the children were found to be able to match size at 20 months of age, that is, before they can match form. Piaget and Inhelder claimed that the proportional scheme is not fully developed until the child is at least 3 years old. They suggested that children can match sizes at 30 months, but are not completely clear about the relationship between objects. We argue that at 22 months of age children can relate objects with apertures, since they raise up the blocks before getting to the aperture. Further, they can relate sizes to one another from 20-month-old children.

These findings contrast with those of Study III, in which children of this age failed to take account of object size in selecting an object to fit into an aperture. This contrast suggests that the covering task was somewhat easier for children than was the task of fitting an object into a hole, even though the functional, covering role of the box relied on the same geometric relationship as did the fitting property of the aperture. It is possible that children chose an appropriate box not by relating the cube to the box's opening, but by relating the 3D exterior shapes of the cube and the box.

A comparison of performance in the trials with the large and small cubes supports this possibility. Because both boxes could cover the small object but only one box could cover the large object, one would expect children to choose the correct cover more often in the large-cube trials, if they were simply satisfied having the box cover the object. In contrast, children chose the matching box non-significantly more often in the small-cube trials. This finding suggests that infants matched the sizes of the two objects.

If the use of a covering task does account for young children's superior performance, a further question concerns the reason for this effect. If children's greater tendency to match boxes and objects is due to an ability to relate the sizes of two different 3D objects (the cube and the box), without being able to consider the size relation of an object to an aperture, then the children's poor performance in Study III may stem from their difficulty in relating a positive space to a negative space. Another reason why children in this experiment may have shown a greater tendency to match boxes and objects might be that the covers were presented in the same orientation as the object to be covered. In contrast to Study III, therefore, the task required no mental rotation. Future research will address these questions.

General Discussion

Representational problems

This thesis demonstrates that the ability to relate objects to each other undergoes dramatic improvements during the second and third years of life. As is often the case with maturing abilities, the children were extremely motivated and challenged by the spatial puzzles presented. Even when they were not very successful, they loved these tasks. Throughout the studies in the present thesis, the children's motivation was remarkable. Even the 14-month-olds completed almost 70% of the trials although they only succeeded in 20% of them. Nevertheless, it appears that before they manage to coordinate their abilities to master environmental problems like the present ones, a strong desire to explore and control their environment motivates them to continue in spite of the fact that they often fail. As mentioned in a section above, core knowledge theories suggest that infants are born with a quantity of innate knowledge, as some cognitive skills develop earlier (Spelke 2000; Spelke and Kinzler 2007). Like in studies on mastering walking, in which children seemed to recognize that they would soon learn to walk (Joh and Adolph 2006), children in our studies who did not succeed in the task appeared to know that they would soon be able to insert the object into the aperture. Further, the closer they came to success at inserting the object, the more persistent they became. It is quite possible that their high motivation and persistence originates from these innate systems.

The high motivation was remarkable seeing that the children did not manage to put a complex object into the aperture until the end of the second year. Although infants distinguish object size and form well before the end of their first year of life, we see from Study I that fitting objects into apertures was poorly mastered before 22 months of age. Adults are puzzled by the difficulties young children have with the seemingly easy task of fitting an object into an aperture. However, our capacity to solve block and aperture problems quickly and effectively depends on specific skills and a long history of learning. Children must learn about the relationship between 3D objects and 2D apertures, how an object and its projective properties change during rotation, and how to move the object to attain specific object orientations. If the task includes a choice, the child must develop a working memory that can handle two objects and one aperture simultaneously. Furthermore, they must have the ability to inhibit the wrong impulses when there is more than one action alternative. In certain situations, adults may also perform less well in such tasks. Adults find it particularly difficult to

imagine a 2D projective shape of a 3D object, if either the object or the perspective view is unfamiliar (Rock 1974; Pani 1993).

In principle, it is possible to solve the fitting task in two different ways. The subjects could solve the task by either feedback or pre-adjustment. Through trying one solution and adjusting the resulting errors, success could eventually be achieved. It is possible that the youngest subjects in the present set of studies tried this strategy but were not successful. It was only when they adjusted the orientation of the object ahead of time that they were able to insert it into the aperture. When orientations differ, a child must imagine how to rotate an object to make it fit into an aperture. In Study I, the 22-month-old children lifted the manipulated blocks and rotated them so that their horizontal cross-sections corresponded to the orientation of the aperture before they attempted to insert them. Before this age, the children did not make systematic pre-adjustments and were mostly unsuccessful in inserting the objects into the apertures.

The children in our studies have the motor skills to manipulate objects. We can thus conclude that their difficulties with these fitting tasks have a more cognitive origin. To know how to insert an object into an aperture, children have to represent the spatial relationship between the object's 3D shape and its 2D silhouette. Further, for most objects, even those with simple and symmetrical shapes, many such silhouettes exist. For example, a regular cylinder has a circular silhouette from a viewpoint parallel to its major axis, a rectangular silhouette from a viewpoint perpendicular to its major axis, and a family of silhouettes of more complex shapes from other viewpoints. It is not surprising that object recognition is easier when the perspectives are similar (Rudge and Warrington 1991; Tarr and Bülthoff 1995; Tarr and Bülthoff 1998). It should therefore be easier to relate the horizontal 2D silhouette to a standing object than a lying one. This was the case in Study I. Children were more successful with the objects that were standing up than with those that were lying down. This was expected, as the standing objects were presented with the cross-section aligned with the aperture. Children did better with the standing objects than with the lying ones, and that applied to all ages, even to the children who were old enough to understand mental rotation. This is not unique to young children. Research on adults reveals that the more spatially complex the object is, the more understanding is necessary (Shepard and Metzler 1971; Shepard and Feng 1972). Rotating an object mentally over a large angle is more difficult than rotating it over a small angle. The more time it takes the more difficult it is, for children as well as adults. It is expected that objects that fit into an aperture in many ways are easier to mentally rotate to an adequate orientation than are those that fit in few ways, as the simpler objects have more opportunities and hence take less time to fit than the more difficult ones do. This is a problem of shape complexity and the results in our studies support this expectation. The cylinder was much easier to fit than any other object was, as it fit in every possible orientation as long as its longitudinal axis was vertical. The asymmetric triangular shape was the most difficult, as it only had one insertion possibility. In order to insert the object into the

aperture, the object has to be placed over the aperture, its longitudinal axis has to be oriented perpendicular to the aperture, and it has to be oriented in such a way as to make its cross-section correspond to the orientation of the aperture.

In everyday life, objects move constantly in and out of sight. If we were unable to keep the spatio-temporal continuity of an object when it disappeared, the environment would be highly confusing. This is another representational problem young children have to deal with when an object is inserted into the aperture of an opaque box. To discover the spatial properties, children have to anticipate that the object is going out of sight. To rule out the invisibility problem, the hole-fitting task in Study III wanted to avoid the situation of the object moving out of sight. Therefore, it was inserted in a shallow hole. The result was that the young children performed at chance, despite the fact that the object remained visible once it had entered the hole. Thus, the loss of visibility of an object does not appear to play a major role in accounting for the difficulty of the classic hole-fitting task.

Another representational problem is the combination of the positive (the block) and negative (the aperture) spaces. While positive spaces are seen as having clear borders, adults often describe negative spaces as having no definite shape at all, but rather as extending indefinitely behind the borders of the surfaces that enclose them (Rubin 1921; Baylis and Driver 1994; Driver and Baylis 1996; Hoffman and Singh 1997; Peterson 2003). Even though mental transformations do not hinder children's performance, as the results of the negative form and positive tower tasks tell us, the requirement that the shapes of positive and negative spaces be matched does.

Sex differences in spatial ability

The common view is that adult males are more spatially advanced than females are (Voyer 1995). This advantage is, however, much less distinct in children, if at all present (Voyer 1995; Roberts and Bell 2002). Recent data reveals that adult men and women have equivalent cognitive abilities, but slightly different approaches to cognitive problems that can be solved with multiple strategies. In the present work, the girls performed as well as boys. Further, they both performed the task equally fast, with the exception of Study II. In Study II, the boys showed a tendency to insert the blocks more rapidly than the girls once their choice had been made. 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 higher prenatal testosterone levels than by girls who had lower levels. Study II could have been related to hormonal triggered genetic advantage in prenatal development, if it hadn't

been for the other experiments, where no sex differences were found. Thus, the effect obtained by Grimshaw et al. (1995) is probably only indirectly related to mental rotation abilities. These results are in line with recent findings that girls and boys do not differ in their ability to learn about objects, numbers and space (Spelke 2005), but as proposed by Hyde (2005), they may use slightly different strategies in solving problems (von Hofsten and Rönqvist 1988).

In Study II, the boys finished the task faster than girls. That can be due to several things. We have seen that older children take time to pause, while the younger children tend to make decisions based on incomplete information (Gauvain and Rogoff 1989; Szepekouski, Gauvain et al. 1994). We might apply that on the children in Study II. The accepted view is that boys are developmentally less mature than girls (Hiedemann, Joesch, and Rose 2004). Hence, they might act more rashly, while girls take more time to pause and gather information before starting with the task. The problem is that boys do just as well as girls. On the other hand, boys might simply be better and more confident than girls, and that is why they did it so fast. Girls, might be more careful than boys, even though they are able to do the task just as quick as the boys. However, this time difference was only shown in one study. In the other studies, there was no time difference.

Making a choice

Making a child *choose* the appropriate action from two alternatives proved to be more, rather than less, difficult than simply trying to insert one object into one aperture. One outcome could have been that the choice made it easier for the children to appreciate the appropriate alternative partly because of the obvious faulty alternative. As we have seen, this is not the case. The aptitude to choose requires more than mental rotation, the ability to imagine goal states and the understanding of means-end relationships. Also, a choice task requires that either the two 3D objects or the two 2D apertures be evaluated. In Study I, in which the children were asked to insert one object into one aperture, they did remarkably better than in Studies II and III where they were to choose one of two alternatives before insertion. However, after the choice had been made, the children inserted the object just as well as in Study I. It is only at about three years of age that children become able to make a carefully prepared decision. Whereas 22- and 26-month-old children succeeded at the task of fitting a single object into a single aperture, even 30-month-olds made errors on the choice tasks and 20-month-olds were completely at chance.

Just as children failed to insert objects with complicated shapes and little symmetry, their choice performance varied with the symmetry of the object. When they were presented with simple shapes with multiple symmetries, they tended to choose the correct aperture or object. When presented with objects with less symmetry, they tended to fail at the task. In Study I, we found that while 22-month-olds were quite successful with both cylindrical and square blocks, 18-month-olds were only successful with cylindrical blocks. They still failed in about half the trials with the square block. In Study II, it was found that when trying to insert the chosen object, 20-month-olds were quite successful with both cylinders and square blocks (80–85%). Because the round object can fit the base at any orientation whereas the square object must be rotated to one of four precise orientations, the performance of the 22-month-olds is not limited by either mental or physical rotation. Studies of shape representations suggest that it is harder to distinguish between similar shapes than between shapes with a clear distinction (Clements and Battista 1992; Clements, Swaminathan et al. 1999). This corresponds to the result of our studies. Although two-year-old children understand what to do with a triangular form, they are unable to distinguish between different triangular forms. It is not until 30 months that the children are able to choose one shape that matches the aperture. Obviously, 40-month-olds had a better result than the 30-month-olds did, and were more sophisticated, but not even at this age they could choose between blocks of different triangular cross-sections.

Further, the children performed better in the aperture-choice task than in the object-choice task. When choosing between the pair of objects, they had to be clear about the appropriate relationship with the aperture already when grasping the chosen object, but it was somewhat surprising that the difference between the two conditions was not bigger. We conclude that when the choice is between apertures, the decision of where to go can be made during the approach itself. When the object is picked up in the two-aperture condition, the choice can be made on the way to the apertures and the object can be compared with each of them at a closer distance before a choice of aperture is made. However, the children did not seem to be able to take advantage of this possibility. When the object was picked up in this condition, it was transported to one of the apertures as rapidly as was the chosen object in the two-object condition, supposedly more evidence of children's inability to master choice situations.

A choice is not only a question of choosing the appropriate object (a positive response) but also to inhibit the choice of an alternative object (a negative response). As we have already seen, young children lack concentration, tending to make decisions too impulsively based on incomplete information (Vurpillot 1968; Müller, Zelazo et al. 2004; Rennie, Bull et al. 2004). It might be that even when the children were qualified to insert the correct objects, they might have had difficulty inhibiting the

tendency to approach the wrong item. If the child fixated on one of the objects, the tendency to grasp it might have been strong even when he/she knew it was the wrong one, and the wrong one could be chosen even when the child knew the correct answer.

In these experiments, we compared the difficulty of object and aperture choice tasks when the relevant variable distinguishing the two objects or apertures is either *shape* or *size*. Size and shape are interesting variables to consider in choice tasks, because they are relevant to object-aperture relationships in different ways. Although objects can only fit through apertures that are larger than the object itself, the relevant size relations can be determined in many cases (and in all the cases tested here) without any mental rotation of the object. In contrast, shape variations are relevant to an aperture task only at the particular orientations at which an object can be made to pass through an aperture. If mental rotation abilities limit young children's performance in object-fitting tasks, we should expect them to master the effects of size variations prior to shape variations. The children were therefore presented with the task of choosing which objects to fit into an aperture, when the objects differed in either shape or size.

In Study III, the variable *size* was added. To recognize that a nearer retinal picture takes up more space than a retinal picture further away does is important to the object-aperture relationship. Reviews of developmental size problems reveal that before six months of age infants can perceive size irrespective of distance, and compare the relationship between an object and an aperture (Piaget and Inhelder 1956; Granrud, Haake et al. 1985; Slater, Mattock et al. 1990; Spelke, Breinlinger et al. 1992). But even if they know that the retinal images vary with distance, they are unaware of how much they vary (Piaget and Inhelder 1956), and from Study III we see that it is not until 20 months of age that children can compare sizes. This depends not only on maturity, but also on the opportunity to learn and explore one's surroundings, something that adults have been doing for a long time. Size and shape are relevant to object-aperture relationships in different ways. Choice tasks with objects that differ in shape are such that the objects are related to the appropriate aperture only at a particular orientation. Even if objects can only fit through apertures that are larger than the object itself, the relevant size relations can be determined without any mental rotation of the object. We have seen that a lack of mental rotation abilities hinder young children's as well as adult's performance in object-fitting tasks. We therefore expected the children to master the effects of size variations prior to shape variations.

Conclusions

Near the third year of life, a developmental change occurs in children's mastery of blocks and holes. This thesis shows that children have to plan how an object is to be adjusted before executing the action. Before the action is carried out, they must imagine the goal-state, and the procedures to get there. We see that pre-adjustments are necessary for manipulating relational objects and it develops between 18 and 22 months. 14 and 18 months used a feedback strategy, something that does not work for this task. By 22 months, children start to raise the blocks presented to them lying down on the way to the hole. The result shows that the object must be orientated and rotated in such a way as to make its cross-section correspond to the cross-section of the aperture. Before arriving at the aperture, the 22-month-old children moved the objects into a vertical position ahead of time and turned the objects appropriately in the horizontal dimension. Pre-adjustments seem to be essential for being able to insert the block into the hole. If children do not pre-adjust and lean on a feedback strategy they fail to insert the block in the hole. The objects with the more regular cross-sections have more goal positions that fit the aperture, but if the object was not turned to any of these positions ahead of time, the children were still lost.

To choose one out of two objects to be fitted in one appropriate hole demands more planning than when a single object is going to be fitted into a single hole. One must appreciate the alternatives, and one must self-regulate to inhibit the alternative choice. To make a choice was more difficult than we imagined, and it develops quite late. Choosing between two objects is more difficult than choosing between two apertures because one has to decide which one to choose before grasping it. But the difference is rather small and is not dependent on age. Since the children were as rapid when it came to objects and apertures, the result tells us that they tended to make decisions based on incomplete information.

Size and form are relevant to the relation between objects and holes in different ways. The size of an object must always be slightly smaller the size of a hole. However, for size tasks, you do not have to pay attention to mental rotation, whereas the form has to be appropriately oriented to fit into the hole. 15-month-olds cannot match either sizes or forms. 20 months are able to relate sizes but not forms. 30 months can relate both sizes and forms.

Earlier findings have established that males are superior to females in mental rotation. It seems not to be the case in these young children and we found no sex differences related to success in our studies. Yet, in Study II, boys solved the problem faster. Later studies have suggests that men and women cope with spatial tasks differently, but solve them equally well.

At times, adults as well as children have problems with mental rotation. Adults often fail to recognize objects from unfamiliar viewpoints

(Rock 1974; Rudge and Warrington 1991), and overcome this limit by developing knowledge of the appearance of objects from diverse views (Tarr and Bülthoff 1995; Tarr and Bülthoff 1998). But the most difficult part with the hole-fitting tasks seems to stem from the requirement that the positive shape of an object and negative shape of an aperture are to be matched.

Sammanfattning

Att manipulera ett objekt är målet för flera viktiga faktorer i barns utveckling. Förmågan att tänka sig objekt i olika positioner förbättrar i hög grad barnets handlingsförmåga. På det sättet kan de allt mer effektivt relatera objekt till varandra, och planera handlingar som kräver minst två objekt. Vid ett års ålder kan barn stoppa ett objekt i ett hål. Tidigare forskning på att stoppa objekt i hål har enbart fokuserat på start och mål, men har bortsett från vägen emellan. Denna avhandling visar att barn är oförmögna att passa in ett objekt i ett hål om de inte kan tänka sig hur ett objekts olika lägen ser ut under vägen. För att göra det måste man mentalt rotera det manipulerade objektet i rätt passningsposition. Problemet med hur man går till väga med relationen mellan objekt och hål studerades hos 14 till 40 månaders barn med hjälp av en låda, olikformade hål och passande träklossar. Studie I koncentrerade sig på orienteringen av objektet. Studie II och III utökade resultatet till Studie I genom tillägg av ytterligare ett objekt eller ett hål, så att variabeln val tillfördes uppgiften. Resultatet visade att det var stor skillnad mellan 18 och 22 månaders gamla barn i fråga om tillvägagångssättet när det gällde att stoppa objektet i hålet. Att lyckas lösa kloss-hål-problemet var förknippat med att i förväg anpassa orienteringen av objektet. Tjugo och 26 månaders barn anpassade orienteringen av objektet innan objektet nådde målet. Fjorton och 18 månaders barn använde sig av feedback, någonting som inte fungerar för den här uppgiften. På det sättet kan de allt mer effektivt relatera objekt till varandra, och planera handlingar som kräver minst två objekt. Att göra ett val visade sig vara svårare än väntat. Det handlar inte bara om att välja ett alternativ, utan också att inhibera ett annat. Vi fann att förmågan att välja rätt mellan objekt eller hål utvecklas ganska sent. 15 månaders barn kunde varken välja mellan storlek eller form. Vid 20 månader kunde barn välja mellan olika storlekar men inte mellan olika former. Trettio månaders barn klarade de enklare formerna, men inte heller vid 40 månader kunde de klara de svåraste triangulära formerna. Gissningsvis är det för tidigt för barnet att kunna skilja på de olika trianglarna som tillhör samma formkategori. Slutligen ville vi veta vad som var svårast i relationen mellan objekt och hål när det handlade om att undersöka yta och form. När vi jämförde relationer mellan ett objekt (positiv form) och ett hål (negativ form), mellan ett tredimensionellt och ett tvådimensionellt hål, och mellan två tredimensionella objekt, fann vi att det svåraste för ett barn är att relatera positiva till negativa former.

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