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# Auditory Guided Arm and Whole Body Movements in Young Infants

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## 1. Introduction

Can infants use auditory information to guide their movements adequately in space, and if so, to what degree? Perceptual development has mostly been considered through the visual system. Similar to vision, audition provides us with spatial information over extended distances. There is generally little research about the use of auditory information for guided movement in the environment, and the similarity between vision and hearing is narrowly attached to a theoretical framework. Effective action is prospective and supposes the pick-up of predictive perceptual information, so as to prepare the body how, when, and where a movement is to be performed. Studies on the use of auditory information for action are rare. This chapter will describe two studies with young infants where it will be shown that the auditory system is equally important as the visual system to the performance of prospective action in the environment. It will be concluded that the auditory system is best conceived as a functional listening system where auditory information is used as a perceptual source for guiding behaviour in the environment.

## 2. Vision versus hearing

Perception of the environment has mostly been considered through visual information. Similar to vision, audition provides us with spatial information over extended distances. Distance perception by ear under naturalistic conditions is a particularly well-developed human capability (Ashmead et al., 1990; Little et al., 1992; Wightman & Jenison, 1995). Hearing may be even more important than vision in orienting towards distant events. We often hear stimuli before we see them, particularly if they take place behind us or on the other side of opaque objects such as walls.

Auditory information is especially important for guiding behaviour in the environment by lack of visual information, such as with the blind (Millar, 1994). In the absence of vision, auditory localization of events that are behind the listener is thought to be aided by spectral shaping introduced by the ears and head (e.g., Hill et al., 2000), as well as by changes in interaural differences (especially time differences) resulting from head movements (Thurlow et al., 1967; Wallach, 1940; Wightman & Kistler, 1999). There is generally little research about the use of auditory information for guided movement in the environment (Jenison, 1997; Lockman, 1990; Pick, 1990).

According to J.J. Gibson's affordance theory (1979), action is affected by environmental information. Information about the environment can be achieved through different senses

(visual, auditory, haptic, etc.). However, adult studies on the use of auditory information for action are rare. For example, Russell and Turvey (1999) posed the question of whether sighted observers with eyes closed could judge correctly whether a wall was wide enough for unimpeded passage based on perception of the distances between a sound-emitting object. Results indicated a limited form of auditory affordance perception: listeners could perceive, with acceptable tolerance, a sound source's azimuth relative to the body's boundaries. The auditory perceptual ability was affected by the source-to-listener distance and visual preview of the spatial layout. Other studies have confirmed the same, reporting variation in the perception of sound location due to source-to-listener distances (Guski, 1990; Loomis et al., 1993) and an improvement of the ability to auditorily control action with previous visual preview of the spatial layout (Warren, 1978).
Research on auditory perception with infants has been concentrated around sound discrimination and auditory localization within specific action systems. It has been shown that infants already from the moment they are born have the ability to turn their heads toward a sound (Muir et al., 1999; Muir & Field, 1979; Wertheimer, 1961). After a while, infants stop to turn after sounds that require large movement of the head (Bower, 1979, 2002; Muir & Nadel, 1998), partly because of changes in the auditory cortex (Clifton et al., 1981), and because of the muscular strength in the neck being too weak in relation to the gravity force. When the infant is 4-5 months old this discrepancy disappears and the infant will turn the head faster and more precise than in the neonatal period (Muir & Clifton, 1985). Head and eye movements can indicate a sound's direction but they cannot inform about distances. Previous research has shown that sighted infants will reach for sounding objects in the absence of visual clues (Ashmead et al., 1987; Clifton, 1992; Clifton et al., 1991; Litovsky & Clifton, 1992; Morrongiello, 1988; Perris & Clifton, 1988). This ability implies a sense of auditory space, a world in which sounding objects are localized in relation to one's body. By 6 months of age, infants are sensitive to changes in the location of sounds as small as 13-19 degrees (Ashmead et al., 1987; Morrongiello, 1988). By 7 months of age, infants have at least a dichotomous discrimination of auditory space, i.e., within and beyond reach (Clifton et al., 1991; Litovsky & Clifton, 1992). This indicates that infants have the ability to differentiate acoustic information and perform adequately in different action systems.

## 3. Early arm movements

Acting successfully entails perceiving environmental properties in relation to oneself (J.J. Gibson, 1979). Organisms do not perceive objects *per se*, but what these objects afford for action. What any given object affords depends on the size and action possibilities of the perceiver. Affordances are therefore not fixed: they have to be updated during life to accommodate changes in action capabilities and bodily characteristics. This is particularly apparent during infancy, when new skills are constantly appearing and bodily dimensions are changing rapidly (Adolph et al., 1993).
Next, a series of experiments on neonatal arm movements will be described and their possible functional significance for later reaching and grasping will be discussed. Before babies can reach out and successfully grasp objects in the environment, they first have to learn they have an arm and what it can do. It is proposed that arm movements made by young infants during the first four months of life have an important exploratory function, essential for the development of eye-hand coordination. But would neonates also be able to control their arm movements based on sound?

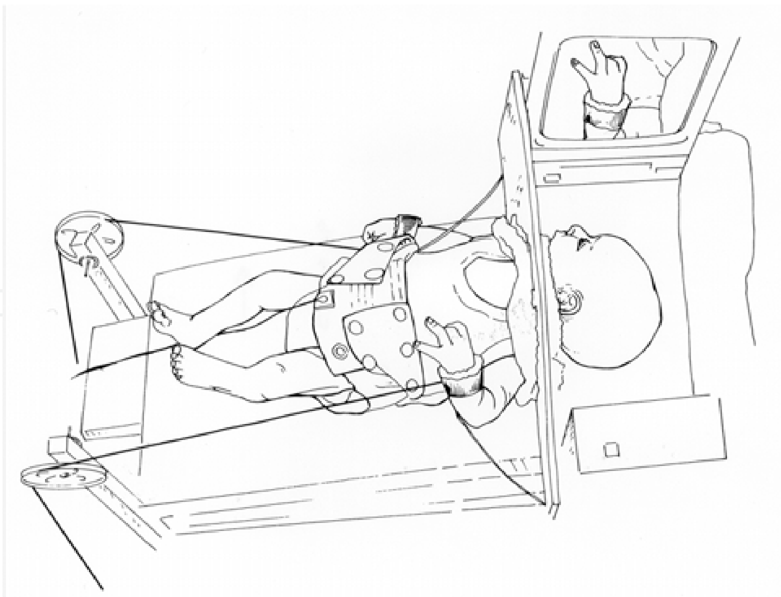

Fig. 1. A newborn baby taking part in the weight-lifting experiment, with sight of the facing hand prevented while the hand on the opposite side of the body is visible in real-time on a small video-monitor.

As a result of the strong influence of the maturation position, newborn babies are still usually considered reflexive organisms, incapable of making voluntary movements. Maturationists consider the existence and disappearance of reflexes as evidence of nervous system growth and development. As maturation of the cortex and the spinal motor nerve pathways proceeds, the cortical centres supposedly inhibit the primitive reflexes. Cortical maturation and the resulting inhibition of reflexive movements are thought to take up most of the four months of a baby's life. Until that time, arm movements made by very young babies are simply dismissed as reflexive, involuntary and purposeless (Van der Meer & Van der Weel, 1995).

Moving a limb or the whole body in a controlled manner requires acting hand-in-hand with gravity and other non-muscular forces, such as the drag of clothing and stiffness of the joints (Bernstein, 1967). As a consequence, movements cannot be represented simply as patterns of efference to the muscles nor in any preprogrammed context-insensitive way. Accurate control requires online regulation of muscular activation based on perceptual information about the dynamics of the limb movement and the external force field, as well as about the movement of the limb relative to objects or surfaces to which it is being guided.

Are neonates capable of such perceptuo-motor control or are their movements to be seen as simply reflexive or due to spontaneous patterned efference to the muscles as is commonly believed? There now is some evidence that newborn babies can move their arms and hands in a purposeful way (Bower et al., 1970; Butterworth & Hopkins, 1988; Von Hofsten, 1982), and we are able to tell that their movements take into account the gravitational and other external forces acting on the limbs (Van der Meer et al., 1995, 1996; Van der Meer, 1997a). However, the question remains whether newborn babies can control their arms based on sound.

### 3.1 Lifting weights in neonates

To test whether newborn babies take account of external forces in moving their limbs, we recorded spontaneous arm-waving movements while the baby lay supine with its head turned to one side (Van der Meer et al., 1995). Free-hanging weights, attached to each wrist by strings passing over pulleys, pulled on the arms in the direction of the toes. The babies were allowed to see only the arm they were facing, only the opposite arm on a video monitor (see Figure 1), or neither arm because of occluders.

The babies opposed the perturbing force so as to keep an arm up and moving normally, but only when they could see the arm, either directly or on the video monitor. Thus, newborn babies purposely move their hand to the extent that they will counteract external forces applied to their wrists so as to keep the hand in their field of view. In addition, newborns move their arms more when they can see them (Van der Meer et al., 1996).

### 3.2 Keeping the arm in the limelight

In order to investigate whether newborns are also able to adjust their arm movements to environmental demands in a flexible manner, we investigated whether manipulating where the baby sees the arm has an influence on where the baby holds the arm (Van der Meer, 1997a). Spontaneous arm-waving movements were recorded in the semi-dark while newborns lay supine facing to one side. A narrow beam of light (7 cm in diameter) was shone in one of two positions: high over the baby's nose or lower down over the baby's chest, in such a way that the arm the baby was facing was only visible when the hand encountered the, otherwise, invisible beam of light (see Figure 2).

The babies deliberately changed arm position depending on the position of the light and controlled wrist velocity by slowing down the hand so as to keep it in the light and thus clearly visible. This suggests sophisticated control of position and velocity of the hand rather than excited thrashing of the limbs, the way neonatal arm movements have been described in the past. However, would newborns also be able to control deceleration of the hand in such a precise manner?

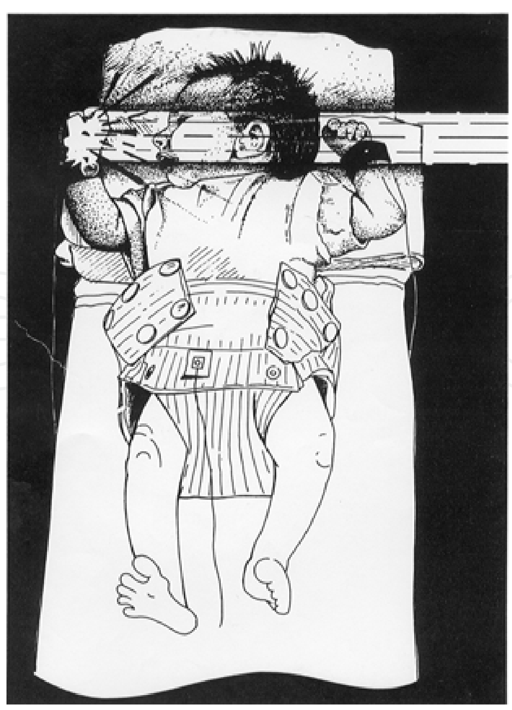

Fig. 2. A 21-day-old baby keeping her arm in the "limelight", a narrow beam of light (7 cm diameter) in an otherwise dark room.

Figure 3 shows a typical position and velocity record of a newborn baby waving its arm. For all instances where the baby's hand entered the light and remained there for 2 seconds or longer, the onset of deceleration (point of peak velocity) of the hand was noted with respect to the position of the light. Surprisingly, in 70 out of all 95 cases (~74%), the babies started to decelerate the arm before entering the light (as in Figure 3), showing evidence of anticipation of, rather than reaction to, the light. On those occasions where the babies appeared not to anticipate the position of the light, more than 70% of these occurred within the first 90 seconds after starting the experiment or changing the position of the light (see Figure 4). Thus, we have shown clear evidence of both learning and memory in newborn babies. By waving their hand through the light in the early stages of the experiment the babies were learning about and remembering the position of the light. This very quickly allowed them to accurately and prospectively control the deceleration of the arm into the light and remain there, while effectively making the arm clearly visible.

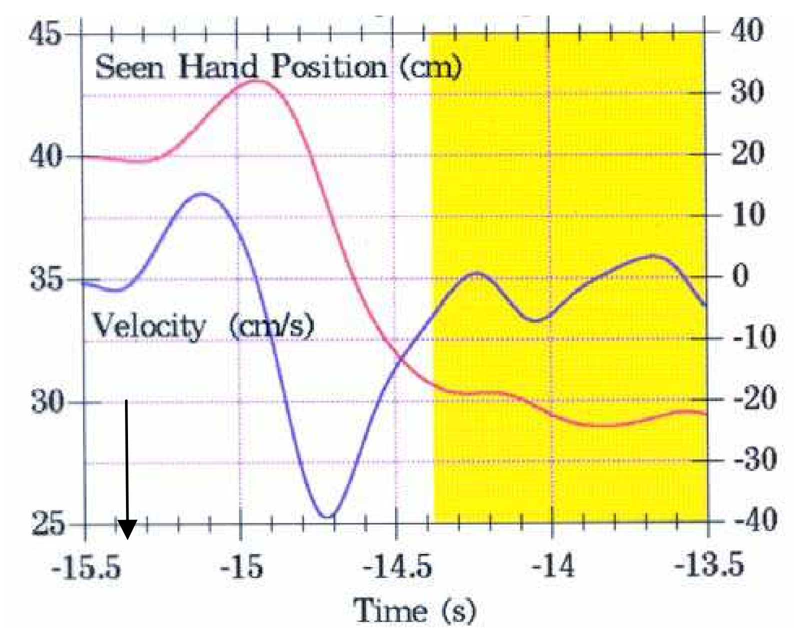


Fig. 3. A typical position and velocity record of a 22-day-old newborn baby waving its arm with light level with chest. The baby could only see the hand clearly in the yellow area, which represents the beam of light. The position trace (red line) indicates that the baby moves its arm 12 cm in the direction of the toes towards the light. The velocity trace (blue line) shows anticipatory deceleration (indicated by the black arrow) starting about 350 ms before the hand enters, and remains in, the shaded visible area. Not that the velocity of the hand in the shaded area is hovering around zero.

### 3.3 Functional significance of early arm movements

It, thus, seems plausible that the spontaneous arm waving of neonates of the kind measured in our experiments is directed and under precise visual control. Neonates can purposely control the position, velocity and deceleration of their arms so as to keep them clearly visible. Their level of arm control, however, is not yet sufficiently developed that they can reach successfully for toys. Young babies have to do a lot of practising over the first four to five months, after which they can even catch fast-moving toys successfully. What could be the functional significance of neonatal arm movements for later successful reaching and grasping?

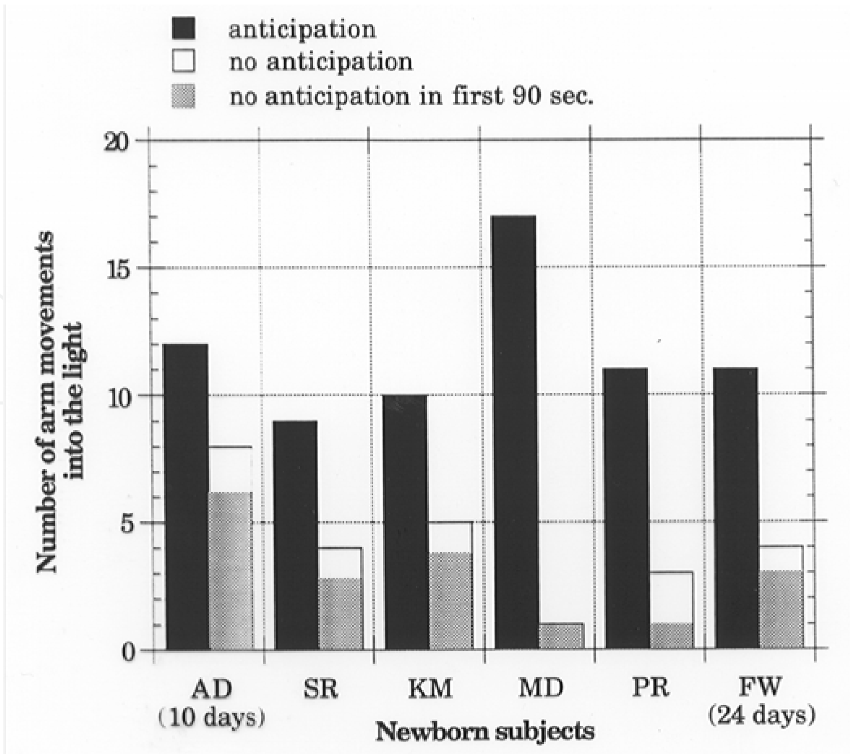


Fig. 4. Total number of cases (n=95) in which the arm was moved into the light and remained there for at least 2 seconds for each newborn subject (increasing in postnatal age from left to right). In a significant number of cases, the babies anticipated the position of the light by starting the deceleration phase of their arm movement before entering the light (black bars). On those 25 occasions where the babies showed no anticipation of the position of the light (white bars), 18 (or 70%) occurred within the first 90 seconds of starting the experiment or changing the position of the light (shaded bars). Note that for 20-day-old MD only one case was recorded where she did not anticipate the position of the light when initiating the deceleration phase of her arm movement into the light, and that this case occurred within one minute into the experiment.

To direct behaviour in the environment successfully, the infant needs to establish a bodily frame of reference for action (Van der Meer & Van der Weel, 1995). Since actions are guided by perceptual information, setting up a frame of reference for action requires establishing informational flow between perceptual input and motor output. It also requires learning about body dimensions and movement possibilities. Thus, while watching their moving arms, newborn babies acquire important information about themselves and the world they move in – information babies need for later successful reaching and grasping beginning at around four to five months of age.

It is widely known that young infants spend many hours looking at their hands (see Figure 5). And so they should, for a vast amount of lessons in practical optics have to be learned in those early weeks before reaching for objects can emerge. First of all, infants have to learn that the hands belong to the self, that they are not simply objects, but that they can be used to touch all sorts of interesting object in the environment. In order to successfully reach out and grasp objects in the environment, infants also have to familiarize themselves with their own body dimensions in units of some body-scaled or, more generally, action-scaled metric (Warren, 1984; Warren & Whang, 1987). In other words, infants have to learn to perceive the shapes and sizes of objects in relation to the arms and hands, as within reach or out of reach, as graspable or not graspable, in terms of their affordances for manipulation.

Fig. 5. A newborn baby boy of only a few hours old is studying his hand intensely.

All this relational information has to be incorporated into a bodily frame of reference for action in those early weeks before reaching for objects "emerges". We have all experienced this process of incorporation, namely when learning new perceptuo-motor skills. For instance, tennis rackets, skis, golf clubs and other extensions of the human body such as false teeth and new cars, first have to be incorporated into our habitual frame of reference, before we can use them to their full potential (Tamboer, 1988). At first, we experience those instruments as unmanageable barriers between the environment and ourselves. However, once incorporated into our "bodily" frame of reference, they increase our action possibilities considerably and are almost regarded as our own body parts.

In this context, it is possible to speculate about the role of early arm movements for distance perception in general. Professor Henk Stassen (1994, personal communication) is a mechanical engineer from Delft University of Technology, The Netherlands. He designs artificial arms for babies who are born with two stumps because of genetic disorders or because their mothers has taken the drug thalidomide in the 1960s during pregnancy to prevent miscarriage. He observed that if you fit babies with artificial arms early (around 2 to three months), they do not seem to have any problems avoiding obstacles as soon as they learn to walk. However, if the arms are fitted to late, the babies will have tremendous problems perceiving distance, and they will initially bump into walls and obstacles when they start walking. J.J. Gibson (1979) suggested that we perceive distance in relation to our own nose length. Stassen's observations would suggest that we scale distance according to our arm length, as within reach or out of reach.

During infancy new skills are constantly appearing and bodily dimensions are changing rapidly. In general, the bodily frame of reference has to be updated during life, to accommodate changes in action capabilities and body characteristics. Sudden changes in action capabilities, as after stroke, show this very clearly, as do rapid changes in body size in pregnancy and adolescence. Teenagers, for example, can be notoriously clumsy; they undergo such sudden growth spurts that their bodily frames of reference need to be updated nearly daily.

Successfully reaching out and grasping objects in the environment requires infants to be familiar with their own body dimensions. As infants wave their arms while supine, they learn about their own body and its dimensions through vision. It seems likely that a fast-growing organism will constantly need to calibrate the system controlling movement, and visual proprioceptive information is least susceptible to "growth errors". This being so, our findings could have practical implications for babies with visual deficits and for the early diagnosis of premature babies at risk of brain damage. If early arm movements have an important function for later reaching, then infants with signs of hypoactivity and/or spasticity of the arms should be monitored closely with respect to retardation of developing reaching and possibly other perceptuo-motor skills. In such cases, early intervention should concentrate on helping the baby to explore its arms and hands, both visually (E.J. Gibson, 1988) and non-visually (Fraiberg, 1977). A simple intervention technique that could be used on babies with a visual deficit is the use of brightly coloured, high-contrast mittens, or a string of bells around the baby's wrists. It is a well-known phenomenon that reaching out is the first developmental milestone that blind babies fail to reach on time. The sound of bells always accompanying that particular proprioceptive feeling when the arms move might enable the baby to establish a stable bodily frame of reference for reaching based on auditory exploration of the self.

### 3.4 Control of early arm movements based on sound

This brings us to the question: Would newborn babies be able to control their arm movements by means of sound? In order to answer this question, newborn babies between three and six weeks of age were placed on their backs with the head in the midline position by means of a vacuum pillow. In this position, both ears were uncovered and available for sound localization (see Figure 6). Miniature loudspeakers of the sort used in telephones were attached to the baby's wrists. The baby's mother was placed in an adjacent, sound proof room where she could see her baby through a window. The mother was instructed to


Fig. 6. A four-week-old baby participating in an experiment on auditory localization of the arms. The mother's voice is played softly over one of the small loudspeakers attached to the baby's wrists.

speak or sing to her baby continuously, while the sound of her voice in real time was played softly over one of the loudspeakers attached to the baby's wrist. In order to hear her mother's voice, the baby would have to move the "sounding" wrist close to the ear, and change arms when the mother's voice was played over the other loudspeaker. The results showed that newborn babies were able to control their arms in such a way that the distance of the left and right wrist to the ear was smaller when the mother's voice was played over that wrist than when it was not. Further analyses showed that there were far more reductions than increases in distance between wrist and ear when the sound was on (see Figure 7). However, when the sound was off the number of reductions and increases in distance between wrist and ear was about the same.

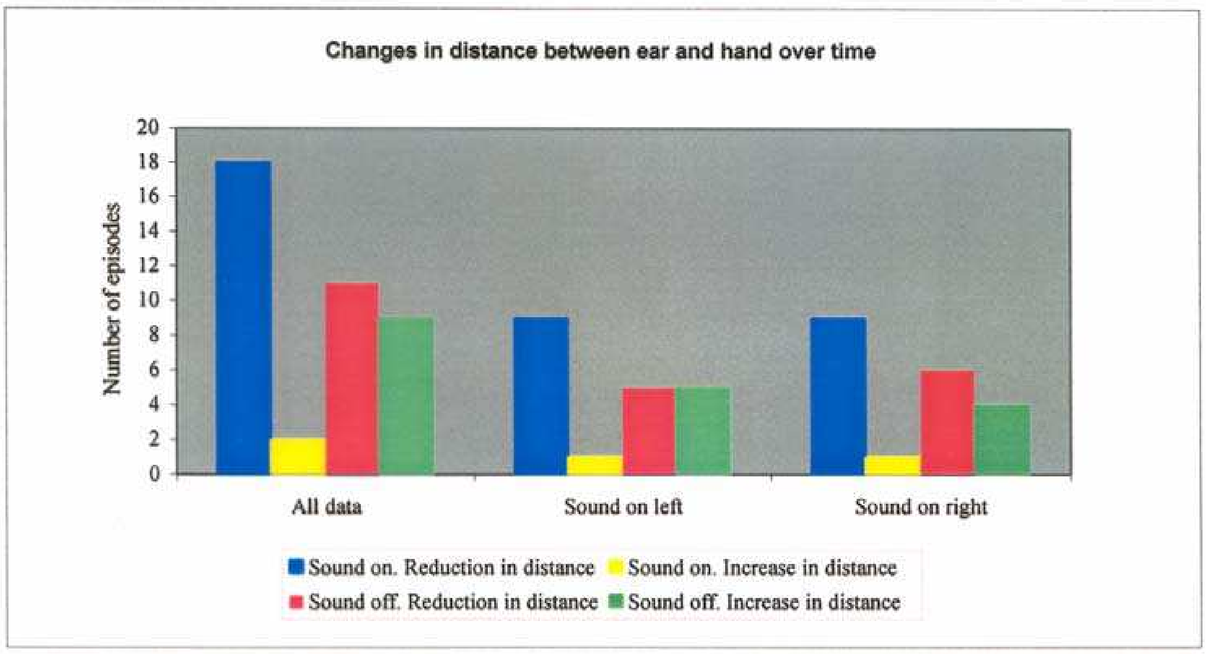


Fig. 7. Changes in distance between ear and hand over time for all data (left), when sound was on the left (middle), and when sound was on the right (right).

Thus, sighted newborn babies can control their arms with help of both sight and sound. This implies that arm movements are not simply reflexive, nor can they be explained away as excited thrashing. Young babies can act intentionally from the start, and they come equipped with perceptual systems that can be used to observe the environmental consequences of their actions. At the same time, an action provides valuable information about oneself. It is this dual process of perceiving oneself and perceiving the consequences of self-produced actions that provides very young infants with knowledge about themselves, in terms of their action capabilities and bodily characteristics. Obviously, during infancy new skills are constantly appearing, and bodily dimensions are changing rapidly. As new action possibilities emerge, infants have to update their perceptions, and vice versa, in a never-ending circular cycle.

## 4. Getting around with light and sound

Adaptive movement in the environment depends on guidance to a destination, avoidance of obstacles, steering and staying on course, and selecting the most economical route to the goal from several alternatives. Effective action supposes prospective control (Gibson & Pick, 2000; Lee, 1993; Von Hofsten, 1993) so as to prepare the body how, when, and where a movement is to be performed. Vision is unquestionably of prime use in locating environmental resources (Gibson & Schmuckler, 1989). Research on visually guided movements in children mainly involves studies where the child moves to a destination with a partly covered goal while the child has to choose between different routes.

A study of detour behaviour by McKenzie and Bigelow (1986) blocked one path to a goal and left one open to find out whether ambulatory infants could choose the shortest route and also show flexible behaviour when the barrier was moved. At 14 months, all infants changed routes successfully and generally followed shorter and more effective routes. Most studies conclude that experience is of significant importance to adaptive performance in this type of task (Caruso, 1993; Hazen et al., 1978; Lockman, 1984; McKenzie & Bigelow, 1986; Pick, 1993; Pick & Lockman, 1981; Rieser et al., 1982; Rieser & Heiman, 1982). A summary of the studies indicates that besides movement experience, other variables such as exploratory movements (Caruso, 1993; Lockman, 1984), the task complexity and motivation to reach the goal (McKenzie & Bigelow, 1986; Rieser et al., 1982), visualization of the layout and the opportunity to get continuous visual information about the goal (Rieser et al., 1982), postural control (Adolph, 2000; Van der Meer, 1997b), and perception of the meaning of the object and event (Adolph et al., 1993; Bertenthal et al., 1984; Ulrich et al., 1990) supposedly affect infants' abilities of adaptive movement in visual perception tasks.

To what extent are infants able to get around the environment by use of auditory perception in a mobility task? Researchers who have examined aspects of perception and action in infants have found that, in general, functionally appropriate perception of what an object affords emerges as the physical capacity to perform that function or task evolves (Gibson et al., 1987; Ulrich et al., 1990).

### 4.1 Auditory guided rotation in infants

Rotation on the stomach is one of the first opportunities infants have to respond to an auditory stimulus behind them. This skill requires infants to use their arms and legs to rotate around their own body axis. It emerges when infants are 6-7 months old (Bobath & Bobath, 1975; Illingsworth, 1973), and allows for a new opportunity to interact with the environment. Emergence of rotation skill requires maturation of both skeletal and neuromuscular systems (Thelen et al., 1987), but the ability to interact adaptively with the environment is not just a result of motor skills. Successful actions require both motor skills and perceptual sensitivity, and of course the ability to integrate the two (Adolph et al., 1993; E.J. Gibson, 1988; Gibson & Schmuckler, 1989; Lee, 1993; Schmuckler, 1993, 1996).

One of infants' first opportunities to move in the environment is by use of rotation skill in a prone position. Use of this skill is also the first opportunity for infants to detect what is behind them, and to perform adequate whole-body movements based on auditory perception. Little is known about infants' rotation skill, and the consequences of using this skill in orienting to objects and individuals. Based on affordance research, we investigated whether infants mastering the rotation skill would use auditory perception for rotation along the shortest way to a sound source, relative to their own position in space (Van der Meer et al., 2008).

Twelve healthy, full-term infants between 6 and 9 months, who mastered the rotation skill in both directions, were included in the study. Figure 8 shows the positions of the infant and the mother in the circle, where the infant performed the rotation and the mother gave

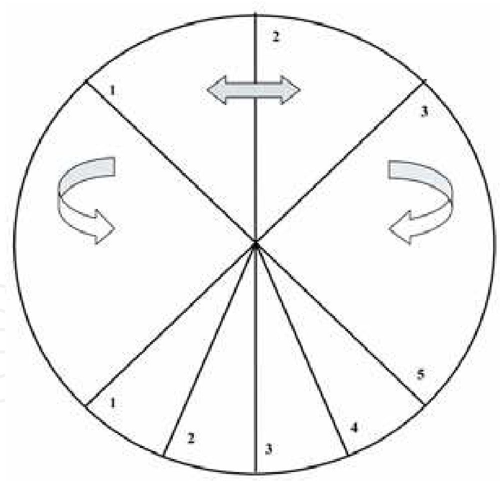


Fig. 8. Illustration of the three different starting positions of the infant (top) and the five different starting positions of the mother (bottom) within the rotation circle. The baby was placed on its stomach with its feet pointing towards the centre of the circle.

continuous auditory stimulation to her baby. To ensure the task remained challenging for the infant, there were three starting positions for the infant and five starting positions for the mother. The coordinate system was constructed with five different angles between the infant's positions and the mother's positions: 90°, 112.5°, 135°, 157.5°, and 180°. Out of a possible 15 combinations, a total of 10 trials were presented in a fixed-random order: four different directional trials where the shortest way would be to rotate to the left and four different directional trials where the shortest way would be to rotate to the right, and two non-directional trials at 180°.

A magnetic tracker system was used to measure the infant's rotations. The system consists of sensors (weighing 25 g each) and a magnetic box which transmits a magnetic field of 3 x 3 x 3 m. The sensors were placed on the infant in the magnetic field (see Figure 9) and their positions (in $x$, $y$, and $z$ direction) and angular rotation (azimuth, role, and elevation) were continuously recorded at 100 Hz.


Fig. 9. A 7-month-old infant wearing a special body and hat placed prone in the rotation circle and participating in the experiment. The magnetic trackers to measure the infant's rotation movements were placed on the head, between the shoulder blades, and on the lower back.

Before each trial the experimenter placed the infant in one of the three starting positions in the middle of the rotation circle, with the feet to the centre. The experimenter sat in front of the infant and maintained its attention, while the mother was instructed to position herself quietly and unseen by the infant in one of five positions, as indicated by the experimenter. Her position was 50 cm behind the centre of the circle (behind the infant's feet). As soon as the measuring started, the experimenter stopped interacting with the infant, while the mother gave continuous auditory stimuli with her voice. The mother was instructed to call her baby in a way that came natural to her, and to continue calling until the baby reached her.

In total, 96 directional trials were recorded. The criterion for rotation was that the infant rotated (both with the head and body) in one direction until the mother was visible for the child. Information about the infant's rotation direction was analyzed through video and the kinematic analyses. In each trial, the rotation direction of the infant was encoded as shortest versus longest way in relation to the position of the infant and the position of the mother. Contrary to expectation, infants did not move their heads before rotating, but in general moved their heads and bodies smoothly in one direction as the trial began.

In case of the directional trials, the babies chose the shortest way in 87.5% of the trials (84 out of 96 trials), indicating that infants between 6 and 9 months use auditory information to move along the shortest way to a goal. Four babies consistently chose the shortest way on all their directional trials, five babies made one mistake, two babies made two mistakes, and one baby made three mistakes (out of 8). Infants chose the shortest way in 75.0% for the largest angle to 95.8% for the smallest angle (see Figure 10). Thus, infants are capable of picking the shortest way to rotate to their mothers, even though they make fewer mistakes with the shorter angles than with the larger angles. This suggests that infants experience increased difficulty differentiating more ambiguous auditory information for rotation.

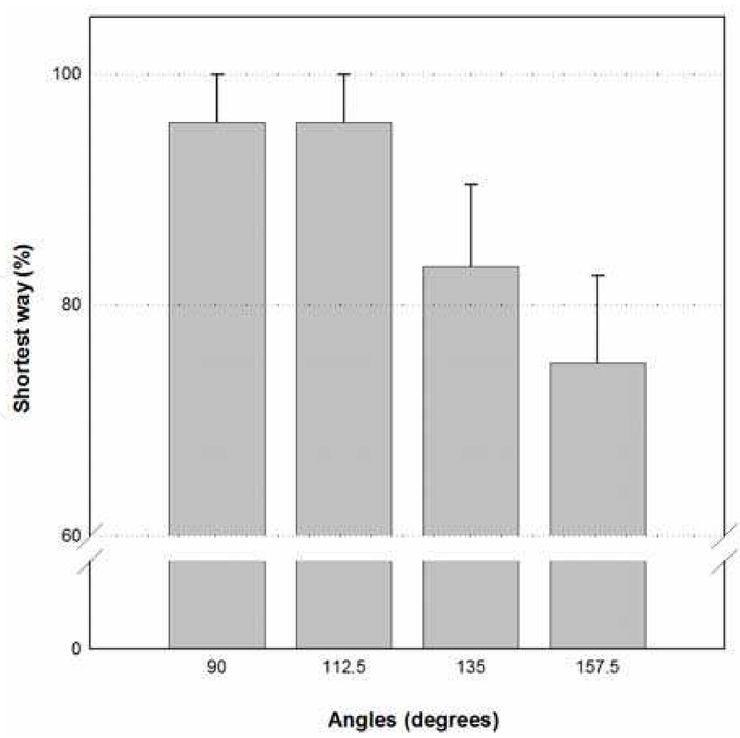


Fig. 10. Average percentages of rotation along the shortest way (including standard error of the mean bars) for the four angle conditions for all twelve participating infants.

To investigate whether infants prospectively adjusted their rotations' angular velocity to the different directional angle conditions, peak angular velocity was calculated for the first couple of pushes that took place within 50% of total rotation time when sight of the mother was unlikely to play a role. Angular velocity was calculated from the azimuth of the marker between the infant's shoulder blades. The azimuth is the direction of the marker referenced to the centre of the rotation circle. The angular velocity is the rate of change of the azimuth. The horizontal and the vertical movements were therefore disregarded in this analysis. As a result, small movements forwards or backwards, but not involving any rotation, showed up as stationary in the data. Figure 11 shows a typical graph of an infant covering an angle of 157.5° towards her mother. An analysis including successful directional trials only showed that the larger the angle between infant and mother, the higher the mean peak angular velocity with which the infants rotated towards her. This finding suggests prospective control of movement, as indicated by a more forceful initial push with the arms and legs in the case of larger angles to be covered.

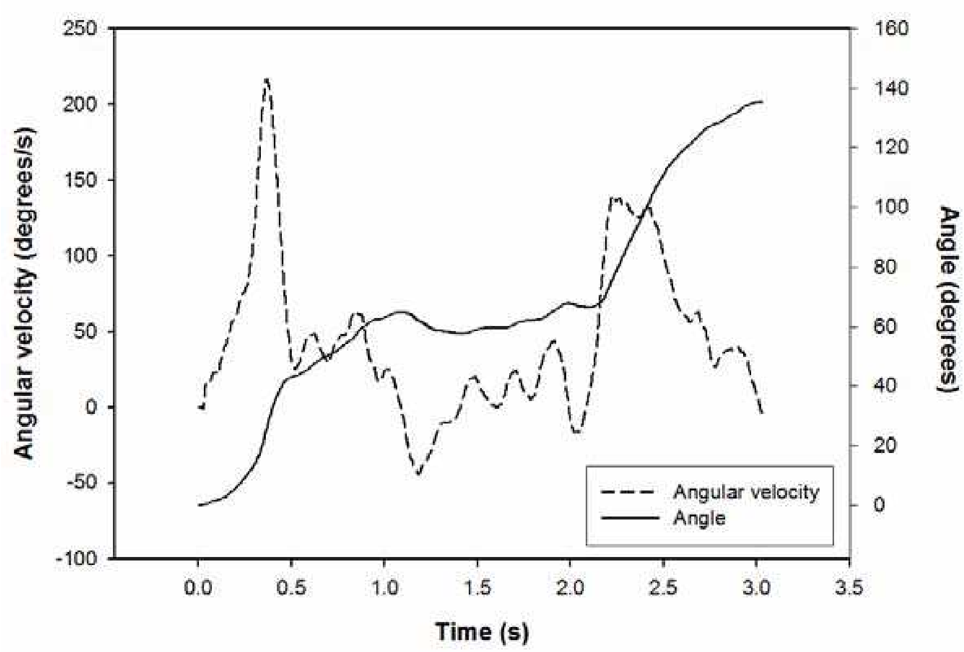


Fig. 11. Illustration of an infant's peak angular velocity (dashed line) during rotation through 157.5° to the left, with a peak angular velocity of 216°/s. Because the angle to the reference point was measured counter clockwise, negative angular velocity indicated clockwise movement. Note that infants typically rotated slightly less than the required angle (here: 140°, solid line, because they would often stop rotating a little short of their mum.

### 4.2 The role of auditory information in guiding whole body movements in space

By manipulating infants' prone rotations with an auditory stimulus from different angles behind the infant, it was found that young infants can use auditory information to guide their movements adequately in space (Van der Meer et al., 2008). In order to be able to rotate along the shortest way to a goal using auditory perception, infants need to be able to locate and specify the direction of the auditory information, and to perceive the angle between themselves and their mother in terms of their own action capabilities. The findings suggest that 6- to 9-month-old infants are capable of controlling their rotation actions effectively and efficiently. Thus, infants' decisions to rotate in a particular direction are not random, but controlled by means of auditory information specifying the shortest way to their mother.

This study is different from other studies in several respects. Infants in the present study were younger, the task was different, and the main perceptual source of information that was used to guide action was auditory instead of visual. In general, use of auditory perception for action has been a neglected research area in the ecological tradition (but see Russell & Turvey, 1999). The present findings corroborate the results of previous studies that newborns and older infants can differentiate between auditory information from left versus right (e.g., Morrongiello & Rocca, 1987; Muir & Field, 1979; Muir et al., 1999; Perris & Clifton, 1988; Wertheimer, 1961), and that they from the age of about six months can localize auditory information for reaching up to 12-14° precisely (Ashmead et al., 1987; Morrongiello, 1988; Morrongiello et al., 1994).

The findings are also in agreement with studies where the task for the infant was to find its way to mum or an object around obstacles with the help of visual perception (e.g., Caruso, 1993; Hazen et al., 1978; Lockman, 1984; McKenzie & Bigelow, 1986; Pick, 1993; Rieser et al., 1982). It can therefore be concluded that sighted infants can use both visual and auditory information for navigation in the environment. The studies by Rieser et al. (1982) and Lockman (1984) have shown that infants are capable of choosing appropriate routes to a goal using vision around the age of 24 and 14 months, respectively. The degree of difficulty of the task, different motor skills and motivation to reach the goal, as well as different degrees of visual information about the goal can explain the age difference for prospective action in these studies. Van der Meer et al.'s (2008) study, on the other hand, indicates that infants as young as 6-7 months will choose the most efficient way to their mother, based on auditory information and using their rotation skill. A possible reason why this has not been reported earlier is because of the fact that the tasks used to study infants' navigational skills have depended on motor skills that develop later in life, such as crawling and independent walking. The use of the mother's voice can also have contributed to the findings. This is a source of auditory information that is easily recognized by infants (DeCasper & Fifer, 1980), and might have increased the infants' motivation to solve the task.

Contrary to expectation, infants did not noticeably move their heads before deciding which way to turn, nor was there any significant latency before a rotation. Slight head rotations as small as 1 or 2° are considered to be helpful in resolving front-back confusions (Hill et al., 2000), a phenomenon where listeners in the absence of vision indicate that a sound source in the frontal hemifield appears to be in the rear hemifield, or vice versa (Wightman & Kistler, 1999). The infants in the present experiment actually might have used vision to resolve this confusion. For example, for a sound source at 135° the interaural time difference is about the same as for a source at 45°, thus solving the task by means of a cross-model elimination process.

## 5. Conclusion

The research reported here shows that newborn babies can use auditory information to control their arms in the environment, and that babies before they start crawling at around 9 months can use auditory information to control their whole body movements in space. Our results can contribute to the understanding of the auditory system as a functional listening system where auditory information is used as a perceptual source for guiding behaviour in the environment.

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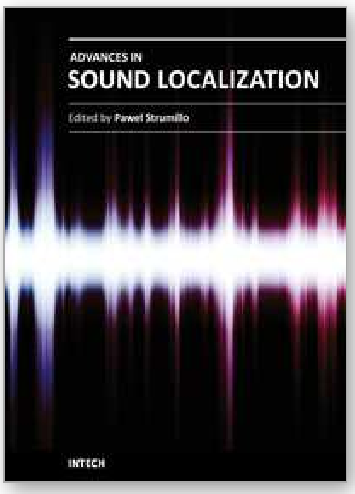


**Advances in Sound Localization**
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Sound source localization is an important research field that has attracted researchers' efforts from many technical and biomedical sciences. Sound source localization (SSL) is defined as the determination of the direction from a receiver, but also includes the distance from it. Because of the wave nature of sound propagation, phenomena such as refraction, diffraction, diffusion, reflection, reverberation and interference occur. The wide spectrum of sound frequencies that range from infrasounds through acoustic sounds to ultrasounds, also introduces difficulties, as different spectrum components have different penetration properties through the medium. Consequently, SSL is a complex computation problem and development of robust sound localization techniques calls for different approaches, including multisensor schemes, null-steering beamforming and time-difference arrival techniques. The book offers a rich source of valuable material on advances on SSL techniques and their applications that should appeal to researches representing diverse engineering and scientific disciplines.

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