Choosing the shortest way to mum: Auditory guided rotation in 6- to 9-month-old infants

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Abstract

The purpose of this study was to investigate the use of auditory information for rotation of the shortest way in twelve 6- to 9-month-old sighted infants. Behavior was manipulated by means of an auditory stimulus presented in four different directional angles (90°, 112.5°, 135°, and 157.5°) to the right and to the left behind the infants, and in one non-directional angle (180°). Infants lay in a prone position and had magnetic trackers fastened to the head and body which measured their rotation direction and angular velocity. The results showed that infants not only consistently chose the shortest over the longest way, but also rotated with a higher peak angular velocity as the angle to be covered between themselves and the goal increased. The results did not show significant preferences for one particular rotation direction. The study can contribute to the understanding of the auditory system as a functional listening system where auditory information is used as a perceptual source for prospectively guiding behavior in the environment.

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1. Introduction

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, Kelso, & Fogel, 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, Eppler, & Gibson, 1993; Gibson, 1988; Gibson & Schmuckler, 1989; Lee, 1993; Schmuckler, 1993, 1996).

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 perception (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.

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A study of detour behavior 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 behavior 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, Lockman, & Pick, 1978; Lockman, 1984; McKenzie & Bigelow, 1986; Pick, 1993; Pick & Lockman, 1981; Rieser, Doxsey, McCarell, & Brooks, 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, 1997, 2000; Van der Meer, 1997), and perception of the meaning of the object and event (Adolph et al., 1993; Bertenthal, Campos, & Barrett, 1984; Ulrich, Thelen, & Niles, 1990) supposedly affect infants’ abilities of adaptive movement in visual perception tasks.

Until now, 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, LeRoy, & Odom, 1990; Little, Mershon, & Cox, 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 behavior 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, Nelson, & Kirkeby, 2000), as well as by changes in interaural differences (especially time differences) resulting from head movements (Thurlow, Mangels, & Runge, 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), and the similarity between vision and hearing is narrowly attached to a theoretical framework (Lee, 1990; Pick, 1990). Therefore, one unanswered question is whether the auditory system plays the same role as the visual system in the perception of affordances, and whether it is equally important to the performance of prospective action in the environment.

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 towards a sound (Muir, Humphrey, & Humphrey, 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, Morrongiello, Kuling, & Dowd, 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, Clifton, & Perris, 1987; Clifton, 1992; Clifton, Perris, & Bullinger, 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° (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.

The aim of this study is to identify to what extent infants are able to perform prospective action by use of auditory perception in a mobility task. Researchers who have examined aspects of perception and action in human 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 (Adolph, 1997; Gibson et al., 1987; Ulrich et al., 1990). Action was manipulated by use of auditory stimulation behind the infants. 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 principles, we set out to investigate whether infants mastering the rotation skill would use auditory perception for rotation along the shortest way to the sound source, relative to their own position in space. This would indicate that infants as soon as they become mobile have the capability to choose an environmental feature that offers the most economical method for acting in relation to themselves, the environment, and the mobility task at hand, based on auditory information.

2. Method

2.1. Participants

Eighteen infants were recruited from local mother and baby health centres, advertisements at the University (NTNU), nurseries, and households with young babies. From these, six (one girl) did not take part in the experiment for the following reasons. During preliminary assessment of their rotation skills (see Section 2.3) three infants were excluded because of performances of rolling over and the total absence of rotation skills. Three more infants were excluded from taking part because they mastered rotation in one direction only. Thus, the study included 12 healthy, full-term infants (7 girls) between 6 and almost 9 months ($M = 7.71$, S.D. = 0.78), who mastered the rotation skill in both directions. In the sample, there was one 6.5-month-old and one 9-month-old, whereas the remaining infants were all between 7 and 8 months of age.

2.2. Apparatus

Fig. 1 shows the positions of the infant and the mother in the circle, where the infant performed the rotation and the mother gave 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°, presented in the following order (with the shortest rotation direction between brackets): (1) 90° [Right], (2) 112.5° [Right], (3) 90° [Left], (4) 135° [Left], (5) 180°, (6) 157.5° [Right], (7) 112.5° [Left], (8) 180°, (9) 135° [Right], (10) 157.5° [Left].

A magnetic tracker system was used to measure the infant’s rotations (Motion Star™ Flock of Birds® from Ascension Technology Corporation). The system consists of sensors (weighing 25 g each) and a magnetic box which transmits a magnetic field of $3 \times 3 \times 3$ m. The sensors were placed on the infant in the magnetic field and their positions (in $x$, $y$, and $z$ direction) and angular rotation (azimuth, roll, and elevation) were continuously recorded at 100 Hz. In order to fasten the sensors to the infant we used Velcro sewn onto a body and a thin cotton hat that was loosely tied under the chin. The hat covered the ears, potentially interfering with sound localization. Three sensors were used: one on the back of the head to record head movements prior to and during rotation, one between the shoulder blades, and one on the lower back (see Fig. 2). The sensor placed between the shoulder blades was mainly used for the analyses. So as to allow the infant complete freedom of movement, the sensors’ cables were hung through a hook in the ceiling. The experiment was also videotaped from above.
2.3. Procedure

Upon arrival at the laboratory, the mother received detailed information about the test procedure and was offered the opportunity to ask questions. All mothers gave their informed consent. First, it was checked whether the infant mastered the rotation skill in both directions on the floor in the reception area. The infant was then dressed in the special body and hat and was placed in a prone position in the rotation circle, where it was given some time to adjust to its environment and the experimenter. After a little while the sensors were placed on the infant, and the experiment started.

Before each trial the experimenter placed the infant in one of 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 placed 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
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.

Each trial lasted for a maximum of 10 s. Trials were recorded continuously, interrupted only briefly to change positions provided there were no other requirements from the infant or the mother. Trials where the baby became inattentive were repeated at the end. This was also done in the case of technical difficulties during data collection. The experiment continued until all ten trials were collected. The babies received a diploma and a T-shirt as thanks for their participation.

3. Results

In total, 96 directional trials were recorded and 23 non-directional trials (one infant rotated only once at 180°, and was therefore not included in the non-directional analysis). The criterion for rotation was that the infant rotated (both with the head and the body) in one direction until the mother was visible for the child. Information about the infant’s rotation direction was analysed through video and the kinematic measurements. 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 soon as the trial began (see Fig. 3). There were just three trials (one at 90° and two at 157.5°) divided over three different participants, where infants turned the head in one direction, before rotating in the opposite direction. In these cases, the actual rotation direction was scored, resulting in the longest way in two instances.

3.1. Selection of shortest versus longest way

Fig. 3 shows a typical trial of an infant rotating to the left along the shortest way to its mother (sound source). In case of the directional trials, the babies chose the shortest way in 87.5% of the trials (84 out of 96 trials). A one-sample t-test showed that infants’ percentages for rotation along the shortest way to the mother were significantly higher than chance, \( t(11) = 10.90, p < 0.001 \). This indicates that infants between 6 and 9 months use auditory information to move along the shortest way to a goal.

![Fig. 3. A typical trial showing the displacement of the three different markers on the infant moving through an angle of 157.5°.](image)
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 Fig. 4). The smaller the angle between infant and mother, the more often infants selected the shortest way. A repeated measures analysis of variance (ANOVA) on infants’ percentages for rotation along the shortest way for the four different angles yielded a significant effect of angle ($F(3,33) = 3.30$, $p < 0.04$), indicating that infants were more likely to choose the shortest way with the smaller than with the larger angles.

3.2. Peak angular velocity of rotation in relation to angle to be covered

To investigate whether the 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 infants’ 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. Fig. 5 shows a typical graph of an infant covering an angle of $157.5^\circ$ towards her mother.

Mean peak angular velocity increased with increasing angle between infant and mother from 106 (S.D. = 39), 126 (S.D. = 29), 149 (S.D. = 29) to 149°/s (S.D. = 43). A repeated measures ANOVA on the subject means for peak angular velocity including successful directional trials only yielded significantly higher values for larger angles between infant and mother ($F(3,33) = 6.11$, $p < 0.003$).

3.3. Preferred direction for rotation

In the directional trials, infants on average chose more often rotation to the right when auditory information was manipulated from the right ($M = 93.8\%$, S.D. = 15.4) than rotation to the left when auditory information was manipulated from the left ($M = 83.3\%$, S.D. = 19.5), but this difference was not significant, $t(11) = 1.33$, ns.

There were two non-directional trials where the angle between infant and mother was $180^\circ$. Out of 11 infants that completed two non-directional trials, two infants chose rotation to the left in both trials, five chose rotation to the
right, and the remaining four infants rotated once to the left and once to the right. In total, infants chose more often to rotate to the right ($M = 63.6\%$, S.D. = 39.3) than to the left in the non-directional trials, but there was no significant preference for rotation to the right, $t(10) = 1.15$, ns. These findings suggest that infants up to 9 months of age have not yet developed a preferred direction for rotation.

4. Discussion

The aim of the present study was to determine whether, and if so, to what degree young infants can use auditory information to guide their movements adequately in space. This was investigated by manipulating infants’ prone rotations with an auditory stimulus from different angles behind the infant. Infants between 6.5 and 9 months of age were able to pick the shortest way to rotate to their mothers, even though they were less prone to make mistakes with the shorter angles (90° and 112.5°) than with the larger angles (135° and 157.5°). This suggests that infants experience increased difficulty differentiating more ambiguous auditory information for rotation. In addition, the findings indicated that peak angular velocity during the first half of the trial was higher when the infants were required to rotate through larger angles. 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.

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 present 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, Fenwich, Hiller, & Chance, 1994).

The present 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. The present 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 present 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. In general, the infants appeared to enjoy our task, although they rarely performed more than 15 rotations.

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°. But the infants could presumably see their mother was not at 45°, thus solving the task by means of a cross-modal elimination process.

In summary, the research reported here shows that infants as young as 6–7 months can use auditory information for prospective action in the environment. Not only did infants select the shortest angle for rotation, they also adjusted their peak angular velocity to the size of the angle that needed to be covered to reach their mother. Rotation in the prone position is arguably one of the first gross motor skills that infants develop, allowing them to change position so as to see what is behind them. Previous findings have reported adequate navigation skills in older infants based on visual and haptic information. The results of the present study 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 behavior in the environment. The findings may have implications for infants with hearing impairments who are unable to benefit from the kind of hearing-guided action measured in our experiment.

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