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Perception of moving, sounding objects by four-month-old infants

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Abstract. Infants and adults were presented with two moving objects accompanied by a single percussive sound. In different experiments, the sound occurred when one object moved through a particular spatial position, when it abruptly changed its direction of movement, or when it made contact with a rigid surface. Infants responded to the sound-object relationship whenever the sound occurred as the object changed direction, irrespective of its impacts with the surface. Adults, in contrast, responded to the sound-object relationship most clearly when sounds were synchronized with impacts. In infancy, perception of auditory-visual relationships thus depends in part on detection of discontinuities in the movement of a visible object.

1 Introduction

Human adults can determine when information from two perceptual modes pertains to one object or event. When we look at an object and listen to a sound, for example, we usually perceive at once whether the object is the source of the sound. On some occasions we may perceive the relationship between an object and a sound by detecting that both are located in the same spatial position. Our perception of sound-object relationships hardly suffers, however, when sounds are separated from their sources, as in the cinema or in a ventriloquist's performance. It appears then that we perceive sound-object relationships by detecting certain temporal correspondences between what we see and what we hear.

To detect a temporal relationship between a sound and a visible object, one must perceive correspondences between certain episodes in the auditory stream and certain states or transformations of the object. Adults appear to perceive many such correspondences. Studies of the 'ventriloquism effect' indicate that adults perceive correspondences between the sight and sound of a beating drum (Radeau and Bertelson 1977), a talking puppet (Jack and Thurlow 1973), and even an active steam whistle (Jackson 1953; see Welch and Warren 1980, for a review). These sounds and objects are related in multiple ways, however, and so the basis for the adult's detection of the auditory-visual relationship is not clear. It is also not clear whether perception of these auditory-visual correspondences depends upon inherent perceptual mechanisms or upon learning about relationships between specific sounds and the objects that produce them.

Like adults, infants of 3 months and beyond have been shown to perceive correspondences between a variety of sounds and objects. For example, infants detect an intermodal relationship when they look and listen to a speaking person (Dodd 1979; Spelke and Cortelyou 1981; Walker 1982), a xylophone that is struck (Bahrick et al 1981), or a wet sponge that is squeezed (Bahrick 1980; see Spelke, in press, for a review). Since each sound was temporally but not spatially related to the appropriate object in these experiments, infants evidently detected the temporal relationship. Further experiments have begun to investigate the kinds of temporal relationships that infants detect. For example, 4-month-old infants have been

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presented with films of two unfamiliar stuffed animals, each of which rose into the air gradually and then fell abruptly to the ground, the two objects falling at different rates (Spelke 1979). While the films were projected side by side, two inanimate sounds—each temporally synchronized with the bounces of one object—were played in turn through a central speaker. When the infants heard a sound, they tended to look to the animal that bounced on the surface in the same temporal pattern. Subsequent experiments indicated that infants responded both to the common rhythm of sounds and movements and to the simultaneity of each sound with a particular bounce (Spelke 1979).

Although these experiments indicate that infants detect a correspondence between sounds and objects that synchronously move into contact, they do not reveal what states of an object must be synchronized with a sound in order for the correspondence to be detectable. There appear to be three possibilities. First, infants may detect a temporal relationship between a sound and object only if the object moves into contact with a surface and the sound is temporally related to the moment of impact. Second, infants may detect relationships between sounds and a larger class of visible events: they may relate a sound to any object that abruptly changes its direction or speed of movement in time with the sound. Third, infants may relate a sound to any object that moves through a particular position in space at the time the sound occurs.

Five experiments with 4-month-old infants were undertaken to investigate each of these possibilities. Five parallel studies were undertaken with adults. In both sets of experiments subjects were presented with moving objects and synchronized sounds. The nature of the sound-object relationship was varied across the experiments to determine what states or transformations of an object are perceived to be related to sound.

The experiments with adults used a procedure based on studies of the ventriloquism effect. They are described in section 7. The experiments with infants used a procedure similar to that of Spelke (1979). An infant was presented with two moving objects, side by side, each synchronized with a distinct sound played from a central location. During a series of preference episodes, the sounds were played for an extended period, one sound at a time. The duration of the infant's looking at the synchronized and at the nonsynchronized objects was assessed. Next, during a series of search trials, the infant's attention was drawn between the objects, one of the two streams of sound was played briefly, and the infant's subsequent looking toward each object was measured. If infants detected the synchrony of each sound with one object, they were expected to look longer at an object when its synchronized sound was played during the preference episodes. They were also expected to look more quickly and more frequently toward each synchronized object during the search trials.

2 Experiment 1

The first experiment was the same as experiment 1 in Spelke (1979), except that the stimulus displays consisted of three-dimensional objects rather than films. Infants viewed two bouncing objects and heard two different percussive sounds. Each sound was synchronized with one object's impacts with a surface. An object always made contact with the surface at the same place and ceased its movement abruptly at the time of impact. Thus, each sound was temporally related to one object in all three of the ways under investigation: it occurred at the time that the object contacted a surface, changed its movement, and passed through a certain location.

2.1 *Method*

2.1.1 *Subjects.* The experiment was conducted with sixteen infants, varying in age from 3 months, 21 days to 4 months, 19 days (mean age: 4 months, 4 days). Two additional infants were eliminated from the study, one because of fussiness, the other because of experimenter error. All the subjects were healthy and were born after a full-term pregnancy. They resided in or near Philadelphia, PA.

2.1.2 *Display materials.* Infants were presented with objects that moved on a puppet stage. The stage was 86 cm wide, 81 cm high, and 59 cm deep. It consisted of a white wooden platform, 23 cm below the infant's eye level, surrounded by tan curtains that covered its sides and a white pegboard surface that served as a background. Below the stage were peepholes through which observers could view the infant.

Two stuffed animals were presented in this stage. One, a yellow kangaroo, measured 37 cm in height and 30 cm at its greatest width. The other, a grey donkey, measured 17 cm in height and 18 cm in width. One animal was positioned 17 cm to the left of center stage, and the other 17 cm to the right. The infant was seated at a viewing distance of 76 cm from the center of the platform.

Each animal was suspended from the ceiling by a transparent monofilament line, threaded through a pulley. Two assistants, standing behind the stage and concealed from the infant's view, were able to raise an animal 31 cm into the air on a vertical path by pulling on the line. The animals took about 1 s to traverse this path, and then they halted abruptly and paused for about 0.5 s. The same assistants lowered the animals to the ground by releasing the line gradually, such that the animals rose and fell at the same speed, halted abruptly on contact with the platform, and paused about 0.5 s before the next cycle of motion began. Each assistant raised and lowered an animal in time to a metronome. One animal was raised and lowered at the rate of 22 cycles min^{-1}, the other animal was raised and lowered at the rate of 20 cycles min^{-1}. Thus, the animals moved at similar rates, but the relative positions of the two animals changed continuously over the course of a session as they both moved concurrently.

Two sounds could accompany the movements of these animals. A dull sound was produced by slapping a hand against an empty semiflexible vinyl box. A metallic sound was produced by tapping a wooden baton against an empty cookie tin. Only one sound was played during a trial, and it occurred at the moment that one of the two animals made contact with the surface. The sound was produced by the assistant who manipulated that animal. That assistant was positioned so that the sound was produced directly behind the center of the puppet stage, midway between the two animals.

2.1.3 *Design and procedure.* Each infant participated in two preference episodes, one eight-trial search episode, and then a third preference episode. During each preference episode, the two objects moved through 26 cycles, accompanied by each of the two sounds in turn. Infants were presented with 10 cycles of one sound, 3 silent cycles, 10 cycles of the second sound, and then 3 more silent cycles. Thus, each preference episode lasted about 75 s. For any given infant, the order of the sounds was the same across the three preference episodes. This order, and the particular sound–object pairing, were counterbalanced across subjects. The lateral positions of the objects were also counterbalanced; for any given infant, however, one animal always appeared on the left and the other on the right.

During each trial of the search episode, a light was flashed repeatedly at the center of the stage while the animals were stationary and suspended in midair. When the baby began to fixate the light, the light was extinguished and the objects began to move. They moved through three cycles, accompanied by one of the two synchronized sounds. After the third cycle the animals returned to their positions in midair and the light began to flash again, initiating the next trial. Each search trial therefore

lasted about 9 s, starting with the moment the baby looked at the light. An infant received four trials with each sound. These trials were presented in a different random order for each subject.

2.1.4 *Dependent measures.* Two observers continuously recorded an infant's visual attention to the object on the left and to the object on the right, without knowing which object was synchronized with a given sound. Both observers independently recorded all looks in both directions. Looking was recorded by pressing buttons that activated pens on an event recorder. The onset of every sound was also recorded, so that the beginning of each preference episode or search trial could be determined from the event record. Interobserver agreement (the proportion of time coded on which the observers both judged that an infant was or was not looking in a particular direction) averaged 86%. Only the record produced by the more experienced member of each pair of observers was analyzed.

The event records were coded by assistants who were ignorant of the sound–object pairings for each baby, For each preference episode, they calculated the duration of looking to each of the objects. The total durations of looking at the synchronized object and at the nonsynchronized object were then calculated across the three preference episodes. The difference in looking times to the synchronized object versus the nonsynchronized object was analyzed by a t test. In addition, changes over time in differential looking at the synchronized and nonsynchronized objects were assessed by calculating difference scores for each preference episode and trial, and by performing a 3 (Episode) $\times$ 2 (Trial) repeated measures analysis of variance (ANOVA) on these difference scores.

In the analysis of the search episode, a trial was eliminated if the infant looked away from the light and toward one of the objects before the sound began. An average of 6.4 trials remained for analysis (range: 3 to 8). Four measures of the infant's tendency to look to a sounding object were calculated from these trials. These are the measures that have been used in all previous studies employing this method (Spelke 1979, 1981). (i) *First look*: the number of search trials on which the infant looked first, after sound onset, at the synchronized object. Such a look was counted only if it occurred within 10 s after sound onset. (ii) *Eventual look*: the number of trials on which an infant looked (first or second) at the synchronized object within 10 s, and similarly for the nonsynchronized object. (iii) *Latency*: the mean latency of looking to the synchronized and to the nonsynchronized object, averaged over all the search trials. If no look at a given object occurred within 10 s, a latency score of 10 was assigned to that trial. (iv) *Duration*: the mean length of looking at the synchronized and at the nonsynchronized object, averaged over all the search trials. If no look at a given object occurred within 10 s, a duration score of 0 was assigned to that trial. These measures were analyzed by t tests comparing looking at the sound-specified and the nonspecified objects.

2.2 *Results*

Table 1 presents the duration of looking at the synchronized object and at the non-synchronized object during each of the preference episodes. Infants looked reliably longer at the synchronized object ($t_{15} = 3.36$, $p < 0.01$). This tendency did not change over the three preference episodes or over the two trials within an episode (all values of $F_{1,15} < 1.1$, not significant).

Results of the search test appear in table 2. Infants searched reliably for the synchronized object. They looked to that object first and eventually on more trials; they also looked at that object more quickly and for a longer duration.

Table 1. Preference episodes, Experiment 1.

Episode	Sound	Synchr.	Nonsynchr.
1	1	15.89	8.61
	2	14.39	10.26
2	1	12.52	9.89
	2	12.48	10.70
3	1	12.45	8.86
	2	9.84	9.99

Table 2. Search test, Experiment 1.

Search measure	Synchr.	Nonsynchr.	t_{15}
First look	4.19	2.19	2.83*
Eventual look	5.75	4.56	4.29*
Latency	2.59	4.77	4.56*
Duration	4.11	2.52	4.82*

*$p < 0.01$

2.3 *Discussion*

Infants detected the relationship between a sound and an object that moved synchronously into contact with a surface. They responded to this relationship by looking preferentially at an object when its synchronized sound was played for an extended time. They also responded to this relationship by turning to look toward an object when its synchronized sound was played briefly.

This experiment replicates the finding that infants detect an auditory–visual relationship when sounds accompany the impacts of a moving object (Spelke 1979). In this study, as in its predecessors, each sound was predictably related to the impacts, the pattern of movement, and the position of the synchronized object. The next experiments attempted to determine which of these correspondences are detected by infants.

3 Experiment 2

This experiment was undertaken to investigate whether infants would detect a relationship between a sound and an object that abruptly halted its movement, with no impact, at the time the sound occurred. The object always halted in the same location but without contacting any other object or surface. The experimental display for this study was the same as that of experiment 1 in all respects but one: sounds occurred not when an object contacted the surface but when it stopped moving abruptly in midair.

3.1 *Method*

The sixteen infants in this experiment ranged in age from 3 months, 24 days to 4 months, 22 days (mean age: 4 months, 5 days). Four additional infants were replaced, one because of fussiness and three because of experimenter errors. Infants viewed the same objects as in experiment 1, moving in the same manner. In this experiment, however, a sound was produced at the moment that an object abruptly ceased rising into the air. Sounds were not systematically related to either object's impacts with the surface.

The design, procedure, and analysis were the same as in experiment 1. On the search test, an average of 5.0 search trials (range: 2 to 8) remained for analysis after the elimination of trials on which infants looked at an object before the sound began. Interobserver agreement throughout the session averaged 86%.

3.2 *Results*

Table 3 presents the duration of looking to the synchronized and the nonsynchronized objects during the preference episodes. Infants looked longer at the synchronized object ($t_{15} = 1.88, p < 0.05$). This preference declined over the course of the three episodes ($F_{1,15} = 4.74, p < 0.025$). The analysis of variance revealed no other significant effects (values of $F_{1,15} < 1$). During the search test, infants' looking was also affected by the sound–object relationships (table 4). Infants looked first and eventually more often at

the object that ceased moving when the sound occurred. They also looked to that object more rapidly and for a longer duration.

Further analyses compared the results of experiments 1 and 2. A 2 x 3 x 2 x 2 mixed factor ANOVA was performed on the looking-time data from the preference episodes of the two studies. Experimental condition (impacts versus no impacts accompanying sounds) was the between-subjects factor. The three within-subjects factors were Episode, Trial, and Object (synchronized versus nonsynchronized). The only significant effects in this analysis were a main effect of Object ($F_{1,\ 15} = 11.04$, $p < 0.01$), and a main effect of Episode ($F_{1,\ 15} = 10.04$, $p < 0.01$). Infants tended to look longer at the synchronized object than at the nonsynchronized object, and they tended to look less at the two objects toward the end of the session. There were no reliable differences between the experiments. In particular, the interaction of Experimental condition with Object did not approach significance ($F < 1$). Infants in both experiments tended to prefer the synchronized object.

Separate 2 (Experimental condition) x 2 (Object: synchronized versus non-synchronized) ANOVAs compared the performance of infants in the two experiments on each of the four search measures. Not surprisingly, all four analyses revealed a significant main effect of Object (all values of $F > 16$, $p < 0.01$). This effect interacted with Experimental condition only in the analysis of the eventual look measure ($F_{1,\ 30} = 5.62$, $p < 0.05$). The tendency to look eventually at the synchronized object was somewhat greater in experiment 1 than in experiment 2. In all other respects, performance in the two experiments was the same.

Table 3. Preference episodes, Experiment 2.

Episode	Sound	Synchr.	Nonsynchr.
1	1	15.99	7.91
	2	12.56	10.41
2	1	12.99	9.84
	2	11.08	12.61
3	1	11.16	8.64
	2	9.26	10.31

Table 4. Search test, Experiment 2.

Search measure	Synchr.	Nonsynchr.	t_{15}
First look	3.06	1.88	3.34^{**}
Eventual look	4.75	4.38	1.86^{*}
Latency	2.57	3.96	2.99^{**}
Duration	4.22	2.83	3.75^{**}

$^{*}p < 0.05$, $^{**}p < 0.01$.

3.3 *Discussion*

The infants in experiment 2 detected the relationship between a sound and a visible object that synchronously changed direction in a constant position in midair. This finding suggests that infants relate percussive sounds to a broader class of visible events than those involving impacts. They appear to relate such sounds to any abrupt change in the movement of an object. We cannot yet conclude, however, that impacts have no special status for infants. If two visible objects both changed their movement in time to a sound and only one of them made an impact with a surface at that moment, it is possible that infants would perceive the sound as more strongly related to the object making an impact. That possibility was tested in experiment 3.

4 Experiment 3

In this experiment, the two objects moved up and down as in the previous studies. At the top of the trajectory they halted in midair; at the bottom they halted on contact with the surface of the stage. The objects moved, however, in synchrony with each other: as one object halted on contact with the surface, the other simultaneously halted in midair. Each sound was synchronized with one object's impacts and the other object's halting in midair. If infants perceive sounds as related to impacts, then they should look to the object that contacted the surface in time

with a sound. If infants perceive sounds as related equally to any change in an object's movement, then the subjects should have looked equally at the two objects while hearing each sound.

4.1 *Method*

The sixteen participants ranged in age from 3 months, 21 days to 4 months, 21 days (mean age: 4 months, 4 days). Eight additional infants were eliminated, three because of fussiness and five because of experimenter errors.

Although the objects moved as in the previous studies, the mechanism controlling their movement was different. The objects were suspended by a monofilament line from opposite ends of a rod, which was in turn suspended from the ceiling, out of view. An assistant rotated this rod back and forth about its center, through a small arc. When the left end was rotated to its highest position, the animal on the right contacted the floor of the stage and the animal on the left halted abruptly in midair. As the right end of the rod then moved from the lowest to the highest position, the animal on the right rose into the air and the animal on the left fell to the ground. The rate of rotation, timed by a metronome, was 21 cycles min^{-1}: approximately the same rate as in the previous studies. The rate of motion, the extent of the motion, and the duration of pausing at each end of the trajectory were the same as in those studies.

The sounds were produced by a second assistant, who stood behind the center of the puppet stage. This assistant could see the ends of the rod as they were rotated to their highest position in the air. One sound was produced when the left end of the rod reached this position: it was synchronized with the impacts of the animal on the right. The other sound was produced whenever the right side of the rod reached this position, in synchrony with the impacts of the animal on the left.

The design, procedure, and analysis were as in the previous studies. An average of 5.2 search trials were scorable for each infant (range: 2 to 8). Interobserver agreement averaged 75%.

4.2 *Results*

Looking times during the preference episodes are given in table 5. The duration of looking at the object whose impacts were simultaneous with a sound was no greater than the duration of looking at the object whose halts in midair accompanied the sound ($t_{15} < 1$). The analysis of variance revealed only a marginally significant effect of Episode on relative looking times to the impacting and nonimpacting objects ($F_{1,15} = 3.10$, $p < 0.10$). Infants tended to look at the object with synchronized impacts more during the first episode than during the other episodes. The analysis revealed no other effects (values of $F_{1,15} < 1$).

The results of the search test are given in table 6. Patterns of looking at the two objects did not differ reliably by any search measure. On hearing a sound, infants were as likely to look to the object that had just halted in midair as to the object that had just contacted the surface.

4.3 *Discussion*

The results of this experiment confirm the conclusion from experiments 1 and 2. Infants appear to relate an abrupt sound to abrupt changes in an object's movement, whether or not those visible changes are accompanied by impacts. There is no evidence that infants perceive a stronger auditory–visual relationship when an impact accompanies the sound. Infants looked equally at the two objects moving in synchrony with the sounds, even though only one of the objects contaced a surface at the time each sound occurred.

Taken together, experiments 1–3 indicate that infants can detect a relationship between an abrupt sound and an object that simultaneously moves to a particular

place and abruptly stops moving in that place. In these studies, a sound was predictably related both to the location of an object and to its pattern of movement. Experiments 4 and 5 investigated the separate effects of these two types of relationships.

Table 5. Preference episodes, Experiment 3.

Episode	Sound	Object with impact	Other object
1	1	16.08	11.55
	2	13.99	12.77
2	1	12.84	14.99
	2	12.34	10.99
3	1	9.93	13.41
	2	10.40	6.98

Table 6. Search test, Experiment 3.

Search measure	Object with impact	Other object	t_{15}
First look	2.44	2.38	0.10
Eventual look	4.06	4.19	−0.33
Latency	4.11	3.67	−0.56
Duration	2.68	2.92	−0.65

5 Experiment 4

In experiment 4 we asked whether infants are sensitive to relations between a sound and the position of a visible object. Infants were presented with two objects that moved continuously, with no changes in the speed or the path of their movement. Each object moved smoothly through the air, its trajectory tracing a circle. The rates of movement of the two objects differed slightly, so that the relative positions of the objects changed continuously as the objects were moved at the same time. Each sound was played at the moment that one object passed through a particular position on its circle; the sound was not predictably related to the position of the other object. If infants detect relationships between a sound and the position of a continuously moving object, then the subjects should have looked preferentially at the object synchronized with the accompanying sound.

5.1 *Method*

The sixteen subjects ranged in age from 3 months, 21 days to 4 months, 26 days (mean age: 4 months, 6 days). Five additional infants were replaced, one because of fussiness and four because of errors in procedure

The display consisted of the same objects and sounds as in the previous studies. The animals were each moved through the air in a circle, 22.5 cm in diameter, on the frontal plane. The center of this circle was at the same position as was the midpoint of each object's vertical trajectory in the previous studies, and the circumference of the circle was roughly equal in length to the round-trip distance of the vertical path travelled in the previous research. Thus, the objects appeared in approximately the same positions as in experiments 1–3 and they moved approximately the same distance. Their movements, however, were continuous.

The apparatus was modified to accomplish this movement. The pegboard background of the puppet stage was replaced by a white plywood surface with two separate circular sections that could be rotated from behind. Each object was attached to one of these circular sections by a metal rod which ran from the back of the object to a point near the circumference of the circle. When the circular section was rotated from behind, the animal attached to that section moved in a circular path in midair. The animals remained upright throughout this rotation. They moved smoothly and silently, at a constant speed.

In order to keep the movements smooth, and to prevent the animals from rocking, it was necessary to move the objects at approximately half the speed of the objects in the previous studies. One animal was moved at the rate of 10 cycles min^{-1}, the other was moved at the rate of 11 cycles min^{-1}. Each object was moved by one

assistant, in time to a metronome. The sounds were produced behind the center of the stage. They were identical to the sounds in the previous studies except for their tempo, which was half as fast. One sound was produced whenever the object on the left passed through the leftmost point on its path; the second sound was produced whenever the object on the right passed through the rightmost point on its path. Each sound was produced by the assistant who moved the corresponding object.

The design, procedure, and analysis were as in the previous studies. Since the sound tempo was slower, each episode was approximately twice the length of those in experiments 1–3. Infants received an average of 4.8 usable search trials (range: 2 to 8). They were observed by two assistants whose agreement averaged 89%.

5.2 *Results*

Table 7 gives the duration of looking at the synchronized and nonsynchronized objects during the preference episodes. There was no tendency for infants to look longer at the synchronized object ($t_{15} < 1$). The difference in looking times to the synchronized and nonsynchronized objects did not change reliably over episodes or trials (all values of $F_{1,\ 15} < 1$).

The results of the search episode appear in table 8. There was no reliable tendency to look for a synchronously moving object when its sound was played, as indexed by any of the four search measures.

Table 7. Preference episodes, Experiment 4.

Episode	Sound	Synchr.	Nonsynchr.
1	1	22.68	25.08
	2	23.61	20.61
2	1	20.38	25.91
	2	27.46	18.68
3	1	18.37	18.41
	2	16.29	16.46

Table 8. Search test, Experiment 4.

Search measure	Synchr.	Nonsynchr.	t_{15}
First look	2.56	2.13	1.03
Eventual look	4.44	4.25	0.83
Latency	2.57	3.29	1.26
Duration	3.76	3.09	1.10

5.3 *Discussion*

Infants did not respond to a relationship between a sound and a continuously moving object that passed through a particular position at the time the sound occurred. They looked equally to that object and to a second, nonsynchronized object, both during the preference episode and during the search episode.

Experiment 4 indicated that infants do not respond to a temporal relationship between a sound and an object when the object moves continuously and only its position is related to the sound. It remained possible, however, that sound–position relations have some effect on infants' perception. Infants may not detect a sound–object relationship unless the object changes its movement in a consistent place every time the sound occurs. Alternatively, it was possible that infants detect a sound–object relationship whenever sounds are synchronized with the changes in movement of an object, irrespective of the position in which those changes take place. Experiment 5 was undertaken to distinguish these possibilities.

6 Experiment 5

In experiment 5, sounds were related to changes in movement of an object but not to its position. Infants were presented with two sounds and two objects, each moving along a circular path as in experiment 4. After approximately one complete revolution, each object abruptly stopped moving and reversed direction. The position at which this change occurred varied continuously throughout the experiment.

The objects were not synchronized, and so they changed direction at different times. Each of two sounds was played simultaneously with changes in the direction of movement of one of the objects.

6.1 *Method*

The participants were sixteen infants, aged 3 months, 17 days to 4 months, 27 days (mean age: 4 months, 6 days). Four additional infants were replaced, one because of fussiness, two because of experimenter errors, and one because of failure to obtain any scoreable trials on the search test.

The display consisted of the same sounds and objects as in the other experiments, with the objects mounted as in experiment 4. An object moved clockwise 360° on its circular path, halted abruptly and paused, moved counterclockwise 380°, and then halted and paused again. Clockwise 360° rotations and counterclockwise 380° rotations continued to alternate. The point at which an object reversed direction thus changed over the course of the episode. One object moved at the rate of 10 rotations min^{-1}; the other at 11 rotations min^{-1}. Each movement lasted about 5 s and was followed by a 1 s pause.

Each object was moved by one assistant, who also produced one of the sounds. A sound was produced every time that one object ceased moving. Thus, sounds were heard at approximately 6 s intervals. As in experiment 4, this slower tempo produced preference and search episodes about twice the length of the episodes in experiments 1–3.

The design, procedure, and analysis were as in the previous experiments. Infants received an average of 6.1 usable search trials (range: 2 to 8). Interobserver agreement averaged 83%.

6.2 *Results*

Table 9 presents the results of the preference episodes. There was no difference in looking times to the synchronized and nonsynchronized objects ($t_{15} < 1$). The ANOVA revealed no changes in differential looking at the two objects over episodes or trials (all values of $F_{1,\,15} < 1$).

Results of the search test, however, reveal a clear response to the synchronized object (see table 10). Infants looked first and eventually on more trials to the synchronized object than to the nonsynchronized object. They also looked at the synchronized object with a shorter latency and for a longer duration.

Table 9. Preference episodes, Experiment 5.

Episode	Sound	Synchr.	Nonsynchr.
1	1	24.38	27.55
	2	24.80	24.75
2	1	25.18	24.58
	2	23.51	18.61
3	1	20.07	16.85
	2	16.16	17.80

Table 10. Search test, Experiment 5.

Search measure	Synchr.	Nonsynchr.	t_{15}
First look	4.00	2.13	3.04^{**}
Eventual look	5.63	5.06	1.94^{*}
Latency	2.46	4.77	3.19^{**}
Duration	4.26	2.32	3.13^{**}

$^{*}p < 0.05$, $^{**}p < 0.01$.

6.3 *Discussion*

Infants detected an auditory–visual relationship when sounds were synchronized with changes in the direction of movement of an object, even though those changes did not occur in any consistent place. When a sound was played briefly during the search test, infants tended to look at the synchronized object. This tendency appeared to be as strong in the present experiment as it was in experiment 2, in which changes

in the movement of an object always occurred in the same spatial location. Nevertheless, infants did not look longer at the synchronized object during the preference episodes. We have no explanation for the absence of the preference effect. In previous research, however, the tendency to look longer at a synchronized object during an extended preference test has often been weaker and less consistent than the tendency to look at that object during a search test (Spelke 1979, 1981). In any case, experiment 5 confirms and extends the findings of the previous experiments. When a moving object changes its movement at the time of a sound, infants perceive the sound and object as related.

7 Synchrony detection by adults

Under what conditions do adults perceive a relationship between a sound and a synchronously moving object? Five experiments addressed this question. In each experiment, adult subjects were presented with the displays used in one of the studies with infants. Perception of sound–object relationships was assessed in two ways. First, subjects were asked to indicate which of the two objects in a given display appeared to be more strongly related to each sound. Second, they were asked to point in the apparent direction of each sound to determine whether detection of a synchronously moving object would affect their judgment of the location of the sound.

7.1 *Method*

Eighty undergraduates at the University of Pennsylvania served as subjects: sixteen subjects in each of the five experiments. None of the subjects was familiar with the research on infancy.

The subjects were tested individually in the infant laboratory. They faced the puppet stage from a distance of 145 cm, with the stage floor about 37 cm below eye level. They were told that they would be presented with a display that had been presented to infants, and that after about 2 min they would be asked some questions about it. Then each subject was presented with the objects in motion, accompanied by each of the sounds in succession. Each sound was presented once, for 10 cycles. The order of sounds, the sound–object pairings, and the lateral positions of the objects were counterbalanced across subjects.

After this presentation the subjects were asked to assess the relative degree of relationship between a sound and the two objects on a scale from 1 ("the sound was related more strongly to the kangaroo") to 4 ("the sound was equally related to the two objects") to 7 ("the sound was related more strongly to the donkey"). These judgments were obtained separately for each of the sounds.

After completion of this rating a pointer was positioned with its base 70 cm from the midpoint of the stage. The subjects were told that the display would be presented again, and they were asked to point "in the direction from which you hear the sound to be coming". A sound was played until the subject indicated that he or she had completed the judgment. The judgments of most subjects took under 30 s to complete. Each subject made two sightings for each sound, one with the pointer initially facing 90° to the left and one with the pointer initially facing 90° to the right. The angle of pointing was ascertained by means of a protractor concealed from the subject's view.

For purposes of analysis, each subject was given a single rating score and a single localization score. The rating score was derived by averaging ratings for the two individual sounds. For experiments 1, 2, 4, and 5, a score of 7 was given if the subject judged the sounds to be maximally related to the sound-synchronized object. For experiment 3, a score of 7 was given if the subject judged sounds to be maximally related to the object whose impacts were simultaneous with the sound. Systematic deviations from the neutral rating of 4 were analysed by t tests. The localization

score was calculated by averaging the deviations of the four localization judgments from the midline and toward the appropriate object. Systematic departures from localization at the midline were analyzed by t tests.

7.2 *Results*

Table 11 depicts the results of the rating judgments. The subjects in experiment 1, presented with sounds accompanying the impacts of an object, judged each sound to be related to the synchronized object. The subjects in experiment 2, presented with sounds accompanying the halting of an object in midair, also judged the sounds and synchronized objects as related. The ratings were higher, however, for the subjects in experiment 1 than for those in experiment 2 ($t_{30} = 2.28$, $p < 0.05$). The subjects in experiments 3, 4, and 5 judged each sound to be equally related to the two objects.

Table 12 presents the results of the localization judgments. The subjects in experiments 1, 2, 4, and 5 localized the sounds in the direction of the synchronized object. Those in experiment 3 localized each sound in the direction of the object with synchronized impacts. The bias in localization was greater for the subjects in experiment 1 than for those in experiment 2 ($t_{30} = 2.24$, $p < 0.05$). This bias was also greater in experiment 5, in which sounds accompanied changes in an object's movement, than in experiment 4, in which sounds occurred consistently when an object passed through a particular position ($t_{30} = 4.02$, $p < 0.01$).

Table 11. Adults' ratings of the sound–object relationships.

Display	Rating	t_{15}
Experiment 1	6.12	9.88**
Experiment 2	4.94	2.00*
Experiment 3	4.50	0.74
Experiment 4	4.40	1.35
Experiment 5	4.25	0.60

*$p < 0.05$, **$p < 0.01$.

Table 12. Adults' auditory localization judgments.

Display	Deviation toward appropriate object	t_{15}
Experiment 1	8.88	7.75*
Experiment 2	4.52	2.87**
Experiment 3	6.34	2.53**
Experiment 4	4.58	2.51*
Experiment 5	12.14	12.53**

*$p < 0.05$, **$p < 0.01$.

7.3 *Discussion*

The results of the sound-localization task suggest that the adults tended to detect relationships between a sound and the position of an object, the changes in the movement of an object, and the impacts of an object. Some of these auditory–visual relationships, however, were more compelling than others. A comparison of the bias in sound localization produced by the displays in experiments 1 and 2 indicated that the bias was greater when sounds were synchronized with impacts than when they were synchronized with changes in movement without impact. Moreover, when adults were presented with the display of experiment 3, in which both objects changed their movement at the time of the sound, adults displaced the sound toward the object that contacted a surface whenever the sound occurred. Finally, a comparison of experiments 4 and 5 suggested that sound–movement relationships exerted a bigger effect on localization judgments than sound–place relationships.

The ratings of the strength of each sound–object relationship proved to be a less sensitive indicator of the adult's detection of auditory–visual correspondences, but this measure produced a similar pattern of results. Sounds were judged to be more strongly related to the synchronized object only in the first two experiments. Of these, the relationship was judged to be stronger in the first experiment. These

findings suggest that adults perceived sounds as most strongly related to events involving impacts, and as related to a lesser degree to changes in the movement of an object in a particular place.

8 General discussion

When infants of 4 months watch a moving object and listen to an abrupt inanimate sound, they can sometimes perceive a relationship between the sound and the visible object. They perceive the sound and object to be related if each sound is synchronized with an abrupt change in the movement of the object. Infants do not perceive the sound and object to be related if the sound is synchronized with the smooth movement of the object through a particular position. Moreover, infants exhibit no special tendency to relate a sound to the particular class of events most likely to produce it: events in which an object contacts a surface. In adulthood, the conditions for auditory–visual perception appear to be somewhat different. Sound-localization judgments, as well as ratings of the strength of a sound–object relationship, suggest that adults relate sounds most strongly to an object that abruptly contacts a surface and secondarily to an object that changes its movement or its spatial position without contacting a surface.

The experiments with infants and adults suggest that certain aspects of the adult's perception of auditory–visual relationships depend on learning or maturation beyond the time of early infancy. In particular, it appears likely that children learn that the impacts of surfaces are the most likely causes of abrupt percussive sounds. The experiments with infants indicate, nevertheless, that certain abilities to perceive auditory–visual correspondences are present early in life. Infants of 4 months relate sounds to changes in the movement of an object. This capacity may serve as a basis for subsequent learning about relationships between visible objects and the sounds they produce.

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