Sound Effects: Multimodal Input Helps Infants Find Displaced Objects

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Abstract

Before 9 months, infants use sound to retrieve a stationary object hidden by darkness but not one hidden by occlusion, suggesting auditory input is more salient in the absence of visual input. This paper addresses how audiovisual input affects 10-month-olds' search for displaced objects. In AB tasks, infants who previously retrieved an object at A subsequently fail to find it after it is displaced to B, especially following a delay between hiding and retrieval. Experiment 1 manipulated auditory input by keeping the hidden object audible versus silent, and visual input by presenting the delay in the light versus dark. Infants succeeded more at B with audible than silent objects and, unexpectedly, more after delays in the light than dark. Experiment 2 presented both the delay and search phases in darkness. The unexpected light-dark difference disappeared. Across experiments, the presence of auditory input helped infants find displaced objects, whereas the absence of visual input did not. Sound might help by strengthening object representation, reducing memory load, or focusing attention. This work provides new evidence on when bimodal input aids object processing, corroborates claims that audiovisual processing improves over the first year of life, and contributes to multisensory approaches to studying cognition.

Keywords: infants; object processing; multisensory; audiovisual; dark

Object representation is fundamental to infant cognition, but difficult to measure because infants' behavior is limited. Historically, it was measured with object retrieval. Failure to retrieve hidden objects implied lack of object permanence – knowing that objects exist when no longer perceptible (Piaget, 1954). Today, researchers recognize that retrieval engages multiple constructs that develop during infancy, including memory and attention (e.g., Stedron, Sahni, & Munakata, 2005). Contemporary evidence also illustrates the many task demands affecting retrieval. For example, infants retrieve objects hidden by occluders later than objects that disappear in other ways, such as in darkness (Hood & Willatts, 1986; Piaget). Historically, most research also focused on visual objects (Leslie, Xu, Tremoulet & Scholl, 1998), yet most objects provide multimodal inputs that infants explore with touch, taste, hearing, *and* sight. Multimodal stimulation generates unified, coherent object representations and is fundamental to the development of perception, cognition, and action (Gibson, 1969). Today, researchers study development from an increasingly multisensory approach, but much remains unknown about how multimodal input affects infants' object processing (Bahrick & Lickliter, 2014; Bremner, Lewkowicz, & Spence, 2012). This paper investigates how auditory and visual information affect 10-month-olds' search for displaced objects.

Audiovisual Input Affects Search for Stationary Objects

Auditory input affects search differently depending on visual input and infants' age. When stationary objects are hidden by visible occluders (e.g., covers), infants fail to use sound to find them before 9 months (Bigelow, 1983). Eight-month-olds who saw either an audible or silent object hidden by occlusion retrieved neither object, whereas 10-month-olds retrieved silent objects reliably, and audible ones even more (Moore & Meltzoff, 2008). However, when objects are hidden by darkness, infants under 9 months *do* use sound (e.g., Clifton, Rochat, Litovsky, & Perris, 1991). Six-month-olds who saw an audible or silent object hidden by darkness retrieved the audible object, but not the silent one, whereas those who saw the same objects hidden by occlusion retrieved neither (Shinskey, 2008). Thus, infants under 9 months are more likely to use auditory input to find hidden objects in the absence of visual input. Why?

One explanation is that conflicting visual input from the occluder disrupts infants' representation more than consistent auditory input supports it (Shinskey, 2008). This explanation stems from constructivist perspectives proposing that object representations are weaker from 5-8 months than 9-12 months (e.g., Cohen & Cashon, 2002; Piaget, 1954). Occlusion appears more demanding on weaker representations because it yields conflicting visual input from the occluder where the object was previously visible, whereas in darkness visual input is simply absent (Munakata, McClelland, Johnson, & Siegler, 1997). Older infants with stronger representations may tolerate this conflict better. If younger infants' representation does not persist throughout occlusion, sound would be meaningless, but if it persists in darkness, infants might bind auditory information to the representation, strengthening it further and explaining earlier success with audible objects in darkness versus occlusion (Shinskey).

Alternatively, perhaps infants represent objects uniformly well from 5-12 months, and other immature processes explain uneven performance before 9 months. Insufficient memory might mean infants forget about the object, and sound might remind them of its existence (Moore & Meltzoff, 2008). Fragile attention might make infants more distractible in the light versus dark (Spelke & von Hofsten, 2001), making this reminder less effective in the light with occlusion than in darkness. Evidence on unimodal facilitation of attention in early infancy supports this claim. Young infants who perceive an event through only one sense attend to modality-specific properties before amodal properties (Bahrick & Lickliter, 2014). For example, infants discriminate between faces with visual input earlier than with audiovisual input, and between voices with auditory input earlier than with audiovisual input (Bahrick, Hernandez-Reif, & Flom, 2005; Bahrick, Lickliter, & Castellanos, 2013). Thus, improvements in representations or associated cognitive processes might explain why infants respond to auditory input in the absence of visual input (at 6 months in darkness) earlier than in its presence (at 10 months with occlusion).

Does Audiovisual Input Affect Search for Displaced Objects?

This paper investigates how multimodal input affects search for *displaced* objects. The tasks above measure search for an object remaining stationary in one location, with success by 9 months. However, in AB tasks, 9- to 12-month-olds who retrieve a hidden object from location A more than once often continue searching there even after seeing it hidden at location B (Piaget, 1954). *A-not-B error*s are a steadfast phenomenon in developmental psychology (Smith, Thelen, Titzer & McLin, 1999), despite lack of consensus on their cause. Piaget claimed they reflected an immature object concept (i.e., infants' belief that the object's existence depends on the act of reaching to a specific place). Contemporary accounts disagree. Some maintain that conceptual deficits cannot be excluded (Ruffman, Slade, Sandino, & Fletcher, 2005). However, most invoke other cognitive, perceptual, and/or motor processes (e.g., Smith et al.; Thelen, Schoner, Scheier, & Smith, 2001), especially those underlying executive control of behavior (Diamond, 1985; Marcovitch & Zelazo, 2009; Munakata, 1998). For example, errors require a delay between hiding and retrieval, implicating working-memory load (Harris, 1973). Errors increase when infants look away from B during this delay, implicating selective-attention lapses (e.g., Horobin & Acredolo, 1986). Errors also increase proportionally with the number of previous reaches to A (Landers, 1971), and occur even when the object is visible at B and visibly absent at A (Harris, 1974). These findings implicate motor-memory processes (e.g., Thelen et al.) or response-inhibition immaturity (Diamond). Retrieving displaced objects thus requires not only object representation but also attention, memory, and inhibition. Lapses in these processes, singly or jointly (Diamond), could foster errors. This paper aims not to resolve long-standing debates on the error's cause, but to use the task to study developments in multisensory object processing. Some of these underlying processes might benefit from auditory input, in either the absence or presence of visual input.

Sound might help for several reasons, beyond merely providing a perceptual cue to object location. (Infants still err with visible objects (Harris, 1974), so even more salient perceptual input seems insufficient alone.) First, sound might reduce demands on memory for the object's location (Moore & Meltzoff, 2008). Second, it might focus infants' attention on the object instead of irrelevant stimuli (e.g., Watanabe, Forssman, Green, Bohlin, & von Hofsten, 2012). Third, bimodal stimulation might generate stronger object representations than unimodal stimulation (Shinskey, 2008). For example, 4-month-olds represent visual occlusion better when sound follows the object's trajectory (Bremner, Slater, Johnson, Mason & Spring, 2012). Compared to unimodal object exposure, bimodal exposure also helps 10-month-olds individuate the number of hidden objects in an event (Wilcox, Woods, Chapa & McCurry, 2007). Only one study has tested how sound affects AB search. Blind 1- to 4-year-olds with residual vision for light received AB trials with a visual object that disappeared when it ceased flashing, or an auditory object that disappeared when it ceased sounding (da Rocha Diz, Mauerberg-deCastro, & Romani, 2012). Children erred with visual objects but not auditory ones, suggesting errors may not generalize from visual to auditory objects. Alternatively, blind children may process sound better than sighted infants, given their age and experience with unimodal auditory objects.

Would darkness help? If it helps 6-month-olds find non-displaced objects by reducing demands on representation, memory, or attention, it might similarly help 10-month-olds find displaced objects. Evidence supports predictions that darkness enhances object processing.

Infants show better haptic recognition of objects explored in darkness versus light (Striano & Bushnell, 2005), and infants' and adults' predictive reaching is better for moving objects that were briefly hidden by darkness versus occlusion (Hespos, Gredeback, von Hofsten, & Spelke, 2009). Evidence also supports predictions that darkness enhances memory. Adults retain information better when pre- and post-exposure fields are dark rather than light (Averbach & Sperling, 1961), and monkeys and pigeons remember more in matching-to-sample tasks after delays in darkness versus light (Etkin, 1972; Roberts & Grant, 1978). No one has tested whether darkness helps infants find displaced objects. Only one study has done so with dogs, who retrieved displaced objects more after delays in darkness versus light (Miller, Rayburn-Reeves, & Zentall, 2009). Darkness could likewise enhance the cognitive processes infants use to find displaced objects.

Would sound help more in the absence or presence of visual input? Ten-month-olds seeking displaced objects might be more sensitive to sound in the dark, like 6-month-olds seeking non-displaced objects (Shinskey, 2008) or blind children seeking displaced auditory objects (da Rocha Diz et al., 2012). Suppressing visual input from A might enhance sensitivity to auditory input at B. Alternatively, improvements in multisensory processing late in the first year (Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006) might help 10-month-olds combine the object's auditory input with the occluders' visual input to track the object better than they would with unimodal input. The following studies address these questions.

Experiment 1

This is the first experiment to test how audiovisual input affects infants' search for displaced objects. Infants retrieved an object hidden at A repeatedly before it was hidden at B repeatedly. The hidden object remained either audible or silent. Experiment 1 manipulated darkness during the 5-s delay between hiding and search, as in Miller et al. (2009). Ten-month-olds saw an object hidden in one of four conditions: audible in light, audible in darkness, silent in light, or silent in darkness (Figure 1). Three hypotheses were tested. First, if sound enhances object processing (Moore & Meltzoff, 2008), the audible groups should outperform the silent groups at B. Second, if the absence of visual input enhances processing during the delay (Miller et al.), the dark groups should outperform the light groups. Third, if sound enhances processing more in the absence of visual input, as for 6-month-olds (Shinskey, 2008), interactions should show the audible-dark group outperforming the other three. Alternatively, if sound enhances processing more in the presence of visual input (e.g., Neil et al., 2006), the audible-light group might outperform the others.

Method

Participants. The final sample had 100 ten-month-olds (49 girls; age 9.8-10.9 months; *M* = 10.3), with 25 in each group. Four additional infants were excluded from the audible-light group for fussiness (3) and experimenter error (1), 2 from the audible-dark group for fussiness, 1 from the silent-light group for fussiness, and 4 from the silent-dark group for not retrieving visible objects during familiarisation (3) and fussiness (1). Infants in the final sample completed at least 3 A practice trials, 3 A test trials, and 3 B test trials (see Procedure).

Design. This mixed-measures design presented Audibility (Audible/Silent) and Illumination (Light/Dark) between participants and Location (A/B) within participants. The side of location A/B (Left/Right) was counterbalanced between participants.

Materials. Infants sat on a parent’s lap across the table from the researcher, who operated a lamp by foot. Infrared video recorded all sessions. A glow-in-the-dark ball was used during darkness familiarisation. Occluders were two opaque containers. Infants received an object from one of two sets of 10 toys, identical except one set was audible and the other silent.

Procedure. First, all infants were familiarized with darkness, regardless of Illumination condition. The researcher gave infants the glow-in-the-dark ball, turned off the light for 5 s, and repeated this for five total trials. Second, infants were familiarized with containers. The researcher demonstrated both containers were empty, then placed them upright, 49 cm apart. She tapped between the containers to break the infant’s gaze, then pushed them to the infant (1 s). For this and subsequent trials, she averted her gaze by looking at the table’s center. Infants had 60 s to explore the containers before receiving a second trial. Third, infants were familiarized with retrieving a visible object. Trials were identical to familiarisation trials above, except as follows. The researcher turned the containers on their sides, placing the object inside container A. For the audible groups, she first activated the music by pressing the object's button. Music duration averaged 25.06 s (*SD* = 5.63). For the silent groups, she pressed the button but the object remained silent. Each trial ended when infants contacted the object or 10 s elapsed, whichever occurred first. Thus, the object played music only for the audible groups, throughout the trial and after it ended. Trials repeated until infants contacted the object on two cumulative trials. Fourth, infants received A practice trials with hidden objects and no delay, identical to visible trials above, except as follows. Containers were upright. The researcher presented the object until infants fixated it, pressed the sound button, and hid the object in container A. Thus, the audible groups heard the object play music continuously from before it disappeared until after they searched. Search was defined as the first container contact. Trials repeated until infants searched A on three cumulative trials. Fifth, infants received A test trials, identical to practice trials with two exceptions. First, the researcher waited 5 s between hiding the object and pushing the containers to infants. Second, during the delay, for the dark groups she turned the lamp off to darken the room, turning it back on as she began pushing the containers to the infant. Trials repeated until infants searched A on three trials. Finally, infants received B trials, identical to

A test trials except for location. Thus, the researcher activated the sound for the audible groups but not the silent groups, hid the object at B, and turned off the lights for the dark groups but not the light groups during the 5-s delay. Trials repeated until infants searched B on three trials or received 10 trials.

Measures and Analyses. Each trial was scored with 1/0 for contacting the correct/incorrect container. Proportional scores were created for A and B by dividing the number of correct searches by the number of test trials on which the infant searched (arcsine-transformed to meet homogeneity-of-variance assumptions). Error run was the number of consecutive B trials that infants failed to search B before their first correct search. One observer coded all infants. Another observer, blind to the hypotheses, coded 96/100 infants. Reliability was .92 for both A and B trials. For error runs, Pearson $r = .90$. Accuracy across A trials and B trials were each analyzed with an Audibility x Illumination ANOVA and *t* tests against chance (.50). Non-parametrics analyzed accuracy on the first B trial, which was binomial, and error run, which did not meet homogeneity-of-variance assumptions, $F(3, 96) = 7.79$, $p < .0001$. All tests were two-tailed.

Results

A Test Trials. Accuracy did not differ by condition. ANOVA yielded no main effect of Audibility, $F(1, 96) = .83$, $p = .365$, or Illumination, $F(1, 96) = 1.54$, $p = .217$, and no Audibility x Illumination interaction, $F(1, 96) = 0.19$, $p = .664$ (Figure 2). All groups exceeded chance, $ts(24) = 7.06$ to 12.49, $ps < .0001$. Thus, neither sound nor darkness improved A accuracy.

B Test Trials. Accuracy across B trials differed by condition. An Audibility effect showed infants searched B more for audible ($M = 62\%$, $SE = 5\%$) than silent ($M = 44\%$, $SE = 4\%$) objects, $F(1, 96) = 9.65$, $p = .002$, $\eta^2 = .09$. An Illumination effect showed they searched more after delays in light ($M = 62\%$, $SE = 5\%$) than dark ($M = 44\%$, $SE = 4\%$), $F(1, 96) =$

9.26, $p = .003$, $\eta^2 = .09$. The Audibility x Illumination interaction approached significance, $F(1, 96) = 3.51$, $p = .064$, $\eta^2 = .04$ (Figure 2). Post-hoc tests, Tukey-corrected for multiple comparisons, showed the audible-light group outperformed the other three, *p*s = .001-.005. The other three did not differ, *p*s = .819-1.000. Only the audible-light group exceeded chance, $t(24) = 5.05$, p < .0001. The others performed at chance, *t*s(24) = -.62-.72, *p*s = .481-.544. Thus, sound and light improved accuracy across B trials.

Non-parametric results for the first trial were similar. An Audibility effect showed more infants searched B for audible ($M = 58\%$) than silent ($M = 28\%$) objects, $U(91) = 730$, $z = -2.83$, $p = .005$. An Illumination effect showed more searched after delays in light ($M = 57\%$) than dark ($M = 27\%$), $U(91) = 722$, $z = -2.89$, $p = .004$. The four groups also differed from each other, $\chi^2(3, N = 91) = 15.85$, $p = .001$ (Figure 3). Paired comparisons showed the audible-light group outperformed the silent-dark group significantly, $U(47) = 117$, $z = -3.96$, $p < .001$, and the audible-dark and silent-light groups marginally, *U*s(45-47) = 182-201, *z*s = -1.88—1.87, *p*s = .061. The latter two did not differ, $U(44) = 240$, $z = -0.04$, $p = .967$, but each outperformed the silent-dark group, *U*s(44-46) = 170-184, *z*s = -2.27—2.19, *p*s = .023-.028. Binomial tests confirmed performance was marginally above chance in the audible-light group, $p = .064$, below chance in the silent-dark group, $p < .0001$, and at chance in the other two groups, *p*s = .684-.678. Thus, sound and light improved search on the first B trial. The audible-light group succeeded most and the silent-dark group least.

Error runs at B also differed by condition. An Audibility effect revealed shorter runs with audible ($M = 1.68$ trials, $SE = 0.34$) than silent ($M = 3.20$, $SE = 0.48$) objects, $U(100) = 880$, $z = -2.64$, $p = .008$. An Illumination effect revealed shorter runs after delays in light ($M = 1.94$, $SE = 0.44$) than dark ($M = 2.96$, $SE = 0.41$), $U(100) = 867.00$, $z = -2.73$, $p = .006$. The four groups also differed from each other, $\chi^2(3, N = 100) = 15.46$, $p = .001$ (Figure 4). Paired comparisons showed the audible-light group outperformed the other three, *U*s(50) = 183-197, *z*s = -4.07--2.46, *p*s = .001-.014. The latter three did not differ, *U*s(50) = 258-310, *z*s = -1.07--.06, *p*s = .283-.952. Thus, sound and light decreased error runs.

Discussion

Audibility and illumination did not affect A search. A-trial success across conditions suggests 10-month-olds' representation of non-displaced objects was so robust, there was no scope for sound or darkness to improve it. This finding contrasts evidence that 10-month-olds retrieve non-displaced occluded objects more when they are audible than silent (Moore & Meltzoff, 2008). However, 10-month-olds in that study received only two trials (one audible, one silent) whereas those tested here received A trials until they succeeded six times. This finding also contrasts evidence that sound improves 6-month-olds' search for non-displaced objects hidden by darkness but not those hidden by occlusion (Shinskey, 2008). It suggests that in simpler tasks with non-displaced objects, infants are more sensitive to auditory input in the absence of visual input at 6 months, consistent with evidence that unimodal information appears more salient earlier in the first year of life (Bahrick & Lickliter, 2014), but equally sensitive to combinations of audiovisual input by 10 months.

Audibility and illumination *did* affect B search, addressing the three hypotheses as follows. First, sound helped infants find displaced objects. The audible groups outperformed the silent groups at B, approximating blind children's performance with auditory objects (da Rocha Diz et al., 2012). Sound might help by reducing demands on representation, memory, or attention (addressed further in the General Discussion). Second, suppressing visual input during the delay did not help. The dark groups did not outperform the light groups. Instead, the reverse tended to occur, in contrast to dogs finding displaced objects more after delays in darkness versus light (Miller et al., 2009). Third, sound did not help more in the absence of visual input. Instead of the audible-dark group performing best, the audible-light group performed best - the only group to exceed chance. This novel finding coincides with evidence that infants respond more reliably to bimodal than unimodal input from 8-10 months when localizing targets, consistent with predictions that audiovisual processing significantly improves late in the first year of life (Neil et al., 2006). The General Discussion elaborates on this interpretation.

First, the dark groups' poor performance was questioned. It was unexpected that darkness did not help, given evidence that representing hidden objects is easier in the absence of visual input than its presence (Hespos et al., 2009; Miller et al., 2009). Perhaps the dark groups performed worse because they experienced light-dark-light transitions that the light groups did not: The lights went off for the 5-s delay, then came back on immediately before infants searched. Such discontinuity might disrupt representation, memory, or attention. If so, search should also be worse at A, at least on the first trial, for the same reason. However, there was no illumination effect across A trials. Subsequent non-parametrics also showed equivalent numbers of infants searched A on the first trial after delays in light (M = 89%) versus dark (M = 93%), $U(88) = 930$, $z = -.64$, $p = .546$. Another explanation is that the dark groups saw a double hiding. The light groups saw a single hiding by occlusion with an opaque container, but the dark groups saw this same occlusion followed by darkness. This manipulation did not deter dogs from retrieving displaced objects (Miller et al.), but perhaps for infants it increased the cognitive demands in the dark groups on B trials. It had no effect at A, but representing a doubly-hidden object combined with higher attention and memory demands on B trials might have caused cognitive overload that hindered search, especially when combined with light-dark-light transitions.

Experiment 2

Experiment 2 addressed these two possibilities with modified dark events. First, darkness extended across both the 5-s delay and 10-s search periods so there was only one light-dark transition. Second, transparent containers replaced opaque ones so infants saw a single hiding by darkness. B-trial performance was then compared with Experiment 1's light groups.

Method

Participants and Design. The final sample had 50 ten-month-olds (25 girls; age 10.0-10.5 months; *M* = 10.3), with 25 each in two groups: audible-dark, silent-dark. Four infants were excluded infants from the audible-dark group for fussiness, and 6 from the silent-dark group for fussiness (4), parental interference (1), and side bias (1 who reached consistently to B on A trials). Audibility (Audible/Silent) occurred between participants and Location (A/B) within participants.

Materials. Materials were the same as before, except opaque containers replaced transparent ones, and their rims were circled with 1-cm glow-in-the-dark tape so infants could locate them in darkness.

Procedure. This was the same as before except as follows. First, darkness-familiarisation trials lasted 10 instead of 5 s, to prepare infants for extended darkness on test trials. Second, the final container-familiarization trial occurred in darkness, to acquaint infants with containers marked by glow-in-the-dark tape approaching them in darkness. Third, the researcher could not judge reaches in darkness, so an observer signalled the end of this and subsequent trials by earphone from another room using infrared CCTV. Fourth, on practice trials with visible objects, the researcher presented a glow-in-the dark ball, placed it in transparent container A, and turned off the light. Finally, on all A and B trials with hidden objects, the researcher placed the object in its corresponding transparent container and hid it by turning off the light.

Reliability and Analyses. Two observers (one blind) coded all sessions. Reliability was 1.00 for A trials and .98 for B trials. For error runs, Pearson *r* = .96. Analyses targeted B trials because no differences occurred on Experiment 1’s A trials, and Experiment 2’s motivation was to explain differences at B. Accuracy across arcsine-transformed B trials was analyzed with a 2 Audibility (Audible/Silent) x 2 Illumination (Experiment 1 Light/Experiment 2 Dark) ANOVA and *t* tests against chance. Non-parametric tests analyzed accuracy on the first B trial and error runs.

Results

Accuracy across B trials in Experiment 2's dark groups improved to approximate Experiment 1's light groups. The Illumination effect disappeared, $F(1, 96) = 2.23$, $p = .138$, but the Audibility effect persisted: Infants searched more for audible ($M = 70\%$, $SE = 4\%$) than silent ($M = 44\%$, $SE = 4\%$) objects, $F(1, 96) = 15.07$, $p < .001$, $\eta^2 = .14$. The Audibility x Illumination interaction no longer approached significance, $F(1, 96) = 0.55$, $p = .460$. Accuracy exceeded chance in the audible-dark group, $t(24) = 2.86$, p = .009, but remained at chance in the silent-dark group, $t(24) = -.14$, p = .890 (Figure 5). Thus, light no longer benefitted accuracy, but sound still did.

On the first B trial, however, accuracy in Experiment 2's dark groups remained somewhat poorer than Experiment 1's light groups. The Illumination effect became marginal: Slightly fewer infants searched B in darkness ($M = 38\%$, $SE = 7\%$) versus light ($M = 57\%$, $SE = 7\%$), $U(95) = 903$, $z = -1.94$, $p = .053$. The Audibility effect persisted: More infants searched B with audible ($M = 59\%$, $SE = 7\%$) than silent ($M = 35\%$, $SE = 7\%$) objects, $U(95) = 852$, $z = -2.37$, $p = .018$. The four groups also differed from each other, $\chi^2(3, N = 95) = 9.52$, $p = .023$. Paired comparisons showed fewer infants searched in the silent-dark than audible-light group, $U(47) = 153$, $z = -3.03$, $p = .002$. The remaining comparisons were not significant, *U*s(46-49) = 219-275, *z*s = -1.61--0.31, *p*s = .108-.756. However, binomial tests showed performance remained at chance in the audible-dark group, $p = 1.000$, and below chance in the silent-dark group, $p = .035$ (Figure 5).

Error runs in Experiment 2's dark groups decreased to approximate Experiment 1’s light groups. The Illumination effect no longer approached significance, *U*(100) = 1061, *z* = -1.38, *p* = .169. The Audibility effect persisted: Runs were shorter with audible (*M* = 1.12, *SE* = 0.30) than silent (*M* = 3.10, *SE* = 0.49) objects, *U*(100) = 779, *z* = -3.42, *p* = .001. The four groups also differed from each other, $\chi^2(3, N = 100) = 13.62$, *p* = .003. Paired comparisons showed the silent-dark group trailed not only the audible-light group, *U*(50) = 147, *z* = -3.39, *p* = .001, but also the audible-dark group, *U*(50) = 190, *z* = -2.46, *p* = .014 (Figure 6). The remaining comparisons were not significant, *U*s(50) = 246-283, *z*s = -1.36--.59, *p*s = .175-.552. Thus, light no longer tended to benefit error runs, but sound continued doing so.

Discussion

If Experiment 1’s dark groups performed unexpectedly worse than its light groups because object processing on B trials was disrupted by light-dark-light transitions or by doubly hiding the object with occlusion plus darkness, then minimizing these transitions and hiding the object by darkness alone in Experiment 2 should have decreased this difference. Indeed, these changes eliminated the effect of illumination on accuracy across B trials and on error runs, and reduced it to a marginal one on the first trial. They also eliminated interaction effects benefitting the audible-light group across B trials, and weakened them on the first trial. This suggests that minimizing such transitions and hiding objects by darkness alone decreased cognitive demands on B trials. However, the main effect of audibility persisted. Across experiments, the audible groups outperformed the silent groups across B trials, on the first trial, and in error runs. Thus, Experiment 2’s manipulations diminished the benefit of visual input, but not that of auditory input.

General Discussion

These are the first experiments to test how bimodal stimulation affects infants’ search for displaced objects. Ten-month-olds searched for audible versus silent objects hidden in the light versus dark, first at location A and then at location B. Three hypotheses were tested. First, the audible groups were expected to outperform the silent groups at B (da Rocha Diz et al., 2012). Both experiments confirmed this prediction. Auditory input improved search. Second, the dark groups were expected to outperform the light groups (Miller et al., 2009). Experiment 1, which imposed darkness during the delay between hiding and search, showed the reverse: The light groups performed better. Experiment 2, which imposed darkness during the delay and search phases, eliminated most of these differences, yet did not reverse them. Thus, suppressing visual input did not improve search. Third, interactions explored whether the audible-dark group might perform best if sound remains more salient in darkness at 10 months as at 6 months (Shinskey, 2008), or whether the audible-light group might perform best if multisensory development makes bimodal input more salient by 10 months (Neil et al., 2006). Experiment 1 showed the audible-light group surpassed the other three, but Experiment 2 showed the audible-dark group caught up on most measures when additional factors were controlled. Thus, auditory input improved search similarly in the absence versus presence of visual input.

Sound Helps Infants Find Displaced Objects

Across conditions, 10-month-olds searched B more for audible than silent objects. One explanation is that infants represent objects better with multimodal stimulation, binding auditory and visual input to construct stronger representations than those constructed from unimodal input (e.g., Shinskey, 2008). This interpretation accords with claims that multimodal inputs promote coherent, unified percepts (Gibson, 1969). Stronger representations likely persist better across transformations like occlusion and displacement (Munakata et al., 1997). Two lines of work support this argument. First, reaching-in-the-dark studies designed to test auditory localization show that infants represent the unseen objects generating the sounds. Six-month-olds familiarized with different objects making different sounds later discriminated between these objects in the dark using sound alone (Clifton et al., 1991). Second, multimodal input helps infants individuate objects. When two audible objects share space behind an occluder, infants individuate them using their distinct sounds (Wilcox, Woods, Tuggy, & Napoli, 2006). By 9 months, they use not only property-rich sounds reflecting object structure (e.g., a rattle) but also property-poor sounds like electronic tones (Wilcox & Smith, 2010). Objects in the current studies produced property-poor melodies, yet 10-month-olds' success suggests they bound these to their representation. Thus, multimodal stimulation may generate amodal representations to which infants then bind surface features (Wilcox et al., 2007).

Alternatively, perhaps sound is simply a perceptual cue that eases other cognitive demands, such as attending to or remembering the object's location during the delay. Some evidence suggests sound is not merely a memory aid. Otherwise, infants under 9 months would search more for audible than silent objects like those over 10 months (Moore & Meltzoff, 2008). Adults also encode bimodal objects more robustly than unimodal ones (Delogu, Raffone, & Belardinelli, 2009). Perhaps sound simply oriented infants' attention towards B and away from A. Sound increasingly enhances attention to visible stimuli across infants' first year. Infants detect audiovisual targets faster than auditory or visual ones at 8-10 but not 1-7 months (Neil et al., 2006). Sound also helps infants detect illusory visual contours at 7 but not 5-6 months (Wada et al., 2009). Developments in multisensory processing may explain why 6-month-olds retrieve audible objects more in the absence of visual input (Shinskey, 2008) but 10-month-olds here did not. Unimodal stimulation seems more likely to benefit cognition at 6 than 10 months (Bahrick & Lickliter, 2014). Recent evidence on tactile-visual processing and on perception of gender coherence likewise reveals significant developments in multisensory processing from 6-10 months (Bremner, Mareschal, Lloyd-Fox, & Spence, 2008; Hillairet de Boisferon, et al., 2015).

The current results cannot untangle whether sound cued attention to the object versus merely the container. However, three lines of evidence suggest infants bind auditory features to the object representation itself. First, prior audiovisual experience with the object enhances search after it becomes hidden, even when sound ceases before search begins (Brower & Wilcox, 2012; Goubet & Clifton, 1998). Second, infant spatial-indexing studies (Benitez & Smith, 2014; Richardson & Kirkham, 2004) show that multiple spatially-consistent encounters with an object (i.e., at A) promote binding auditory and visual features into a unified representation that transcends the local context and transfers to new locations (i.e., at B). Third, adult studies show that attending to an object's auditory features co-activates the representation's visual features even when the visual stimulus is absent (Chen & Spence, 2010; Molholm, Martinez, Shpaner & Foxe, 2007). Sound can thus orient attention, which spreads to other features bound to the representation via other modalities, enhancing processing even when the object moves or disappears.

Darkness Does Not Help Infants Find Displaced Objects

Darkness was expected to help 10-month-olds find displaced objects because it helps individuals in similar tasks by reducing demands on representation and memory. Darkness helps dogs find displaced objects, increases other animals' memory, and improves infants' and adults' object retrieval (Hespos et al., 2009; Miller et al., 2009; Roberts & Grant, 1978; Shinskey, 2008). Yet, there was no evidence that it improved 10-month-olds' object processing here. B-trial search was no better in the dark groups than the light groups. Suppressing visual input thus did not demonstrably improve the processes of representation, memory, or attention underlying infants' displaced-object search. Perhaps methodological variations explain differences among findings. Comparing results across studies is difficult due to differences in age, species, target, delay, and visible stimuli. The current experiments tested human infants tracking toys over 5-s delays, during which occluders in the illuminated conditions remained visible. The only other study to explore how darkness affects displaced-object retrieval tested adult dogs tracking food over 5-, 10-, or 15-s delays. During delays, occluders in the illuminated conditions were blocked from sight by a second experimenter holding a barrier, whereas occluders in the dark conditions disappeared when the lights turned off. This double occlusion plus the presence of another experimenter might have disrupted dogs' processing more in the illuminated conditions, yielding better performance in the darkness conditions.

Conclusion

These are the first studies to show that audiovisual input affects infants' search for displaced objects. Sound helped 10-month-olds find objects in the presence or absence of visual input. This result converges with evidence showing that sound aids object processing on several levels from representation to memory to attention (Brower & Wilcox, 2012; Delogu et al., 2009; Neil et al., 2006). It also supports claims that multisensory processing improves significantly across the first year of life, guiding the development of perception, cognition, and action (Bahrick & Lickliter, 2014). However, darkness did not help. Previous studies showed darkness improves performance in infants, adults, and other species, suggesting that suppressing visual input enhances object processing (Hespos et al., 2009; Miller et al., 2009). This benefit does not generalize to 10-month-olds' search for displaced objects. This work provides new evidence on when multimodal input aids object processing, contributing to increasingly multisensory approaches to studying cognition.

References

Averbach, E., & Sperling, G. (1961). Short-term storage of information in vision. In C. Cherry (Ed.), *Information theory* (pp. 202-214). London: Butterworth.

Bahrick, L. E., Hernandez-Reif, M., & Flom, R. (2005). The development of infant learning about specific face-voice relations. *Developmental Psychology, 41*(3), 541-552. doi:10.1037/0012-1649.41.3.541

Bahrick, L. E., & Lickliter, R. (2014). Learning to attend selectively: The dual role of intersensory redundancy. *Current Directions in Psychological Science*, *23*(6), 414-420. doi:10.1177/0963721414549187

Bahrick, L. E., Lickliter, R., & Castellanos, I. (2013). The development of face perception in infancy: Intersensory interference and unimodal visual facilitation. *Developmental Psychology*, *49*(10), 1919-1930. doi:10.1037/a0031238

Benitez, V. L., & Smith, L. B. (2012). Predictable locations aid early object name learning. *Cognition*, *125*(3), 339-352. doi:10.1016/j.cognition.2012.08.006

Bigelow, A. E. (1983). Development of the use of sound in the search behavior of infants. *Developmental Psychology*, *19*(3), 317-321. doi:10.1037/0012-1649.19.3.317

Bremner, A. J., Lewkowicz, D. J., & Spence, C. (2012). *Multisensory development*. New York, NY, US: Oxford University Press. doi:10.1093/acprof:oso/9780199586059.001.0001

Bremner, A. J., Mareschal, D., Lloyd-Fox, S., & Spence, C. (2008). Spatial localization of touch in the first year of life: Early influence of a visual spatial code and the development of remapping across changes in limb position. *Journal of Experimental Psychology: General*, *137*(1), 149-162. doi:10.1037/0096-3445.137.1.149

Bremner, J. G., Slater, A. M., Johnson, S. P., Mason, U. C., & Spring, J. (2012). The effects of auditory information on 4-month-old infants' perception of trajectory continuity. *Child Development, 83*(3), 954-964. doi:10.1111/j.1467-8624.2012.01739.x

Brower, T., & Wilcox, T. (2012). Shaking things up: Young infants' use of sound information for object individuation. *Infant Behavior & Development*, *35*(2), 323-327. doi:10.1016/j.infbeh.2011.12.007

Chen, Y., & Spence, C. (2010). When hearing the bark helps to identify the dog: Semantically-congruent sounds modulate the identification of masked pictures. *Cognition*, *114*(3), 389-404. doi:10.1016/j.cognition.2009.10.012

Clifton, R. K., Rochat, P., Litovsky, R. Y., & Perris, E. E. (1991). Object representation guides infants' reaching in the dark. *Journal of Experimental Psychology: Human Perception and Performance, 17*(2), 323-329. doi:10.1037/0096-1523.17.2.323

Cohen, L. B., Chaput, H. H., & Cashon, C. H. (2002). A constructivist model of infant cognition. *Cognitive Development, 17*(3-4), 1323-1343. doi:10.1016/S0885-2014(02)00124-7.

da Rocha Diz, M.C., Mauerberg-deCastro, E., & Romani, M.F. (2012). Perseveration in congenitally blind children: Effects of luminous and acoustic targets on a modified A-not-B task. *Infant Behavior & Development, 35,* 645-654. doi:10.1016/j.infbeh.2012.07.001

Delogu, F., Raffone, A., & Belardinelli, M. O. (2009). Semantic encoding in working memory: Is there a (multi)modality effect?. *Memory*, *17*(6), 655-663. doi:10.1080/09658210902998054

Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on AB. *Child Development, 56*(4), 868-883. doi:10.2307/1130099

Etkin, M. W. (1972). Light produced interference in a delayed matching task with capuchin monkeys. *Learning and Motivation*, *3*(3), 313-324. doi:10.1016/0023-9690(72)90027-6

Gibson, E. (1969). *Principles of perceptual learning and development*. East Norwalk, CT, US: Appleton-Century-Crofts.

Goubet, N., & Clifton, R. K. (1998). Object and event representation in 6½-month-old infants. *Developmental Psychology*, *34*(1), 63-76. doi:10.1037/0012-1649.34.1.63

Harris, P. L. (1973). Perseverative errors in search by young infants. *Child Development*, *44*(1), 28-33. doi:10.2307/1127675

Harris, P. L. (1974). Perseverative search at a visibly empty place by young infants. *Journal of Experimental Child Psychology*, *18*(3), 535-542. doi:10.1016/0022-0965(74)90131-3

Hespos, S., Gredebäck, G., von Hofsten, C., & Spelke, E. S. (2009). Occlusion is hard: Comparing predictive reaching for visible and hidden objects in infants and adults. *Cognitive Science: A Multidisciplinary Journal*, *33*(8), 1483-1502. doi:10.1111/j.1551-6709.2009.01051.x

Hillairet de Boisferon, A., Dupierrix, E., Quinn, P. C., Lœvenbruck, H., Lewkowicz, D. J., Lee, K., & Pascalis, O. (2015). Perception of multisensory gender coherence in 6- and 9-month-old infants. *Infancy*, doi:10.1111/infa.12088

Hood, B., & Willatts, P. (1986). Reaching in the dark to an object's remembered position: Evidence for object permanence in 5-month-old infants. *British Journal of Developmental Psychology, 4*, 57-65. doi:10.1111/j.2044-835X.1986.tb00998.x

Horobin, K., & Acredolo, L. (1986). The role of attentiveness, mobility history, and separation of hiding sites on Stage IV search behavior. *Journal of Experimental Child Psychology*, *41*(1), 114-127. doi:10.1016/0022-0965(86)90054-8

Landers, W. F. (1971). Effects of differential experience on infants' performance in a Piagetian Stage IV object-concept task. *Developmental Psychology*, *5*(1), 48-54. doi:10.1037/h0031064

Leslie, A. M., Xu, F., Tremoulet, P. D., & Scholl, B. J. (1998). Indexing and the object concept: Developing 'what' and 'where' systems. *Trends in Cognitive Sciences*, *2*(1), 10-18. doi:10.1016/S1364-6613(97)01113-3

Marcovitch, S., & Zelazo, P. D. (2009). A hierarchical competing systems model of the emergence and early development of executive function. *Developmental Science, 12*(1), 1-18. doi:10.1111/j.1467-7687.2008.00754.xMiller, H. C., Rayburn-Reeves, R., & Zentall, T. R. (2009). What do dogs know about hidden objects? *Behavioural Processes*, *81*(3), 439-446. doi:10.1016/j.beproc.2009.03.018

Molholm, S., Martinez, A., Shpaner, M., & Foxe, J. J. (2007). Object-based attention is multisensory: Co-activation of an object's representations in ignored sensory modalities. *European Journal of Neuroscience*, *26*(2), 499-509. doi:10.1111/j.1460-9568.2007.05668.x

Moore, M., & Meltzoff, A. N. (2008). Factors affecting infants' manual search for occluded objects and the genesis of object permanence. *Infant Behavior & Development, 31*(2), 168-180. doi:10.1016/j.infbeh.2007.10.006

Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A PDP model of the AB task. *Developmental Science*, *1*(2), 161-184. doi:10.1111/1467-7687.00021

Munakata, Y., McClelland, J.L., Johnson, M.H., & Siegler, R.S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review, 104,* 686-713. doi:10.1037/0033-295X.104.4.686

Neil, P. A., Chee-Ruiter, C., Scheier, C., Lewkowicz, D. J., & Shimojo, S. (2006). Development of multisensory spatial integration and perception in humans. *Developmental Science, 9*(5), 454-464. doi:10.1111/j.1467-7687.2006.00512.x

Piaget, J. (1954). *The construction of reality in the child.* New York: Basic Books.

Richardson, D. C., & Kirkham, N. Z. (2004). Multimodal events and moving locations: Eye movements of adults and 6-month-olds reveal dynamic spatial indexing. *Journal of Experimental Psychology: General*, *133*(1), 46-62. doi:10.1037/0096-3445.133.1.46

Roberts, W. A., & Grant, D. S. (1978). An analysis of light-induced retroactive inhibition in pigeon short-term memory. *Journal of Experimental Psychology: Animal Behavior Processes, 4*(3), 219-236. doi:10.1037/0097-7403.4.3.219

Ruffman, T., Slade, L., Sandino, J. C., & Fletcher, A. (2005). Are A-Not-B errors caused by a belief about object location? *Child Development, 76*(1), 122-136. doi:10.1111/j.1467-8624.2005.00834.x

Shinskey, J.L. (2008). The sound of darkness: Why do auditory cues aid infants’ search for objects hidden by darkness but not by visible occluders? *Developmental Psychology, 44*(6), 1715-1725. doi:10.1037/a0012836

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review*, *106*(2), 235-260. doi:10.1037/0033-295X.106.2.235

Spelke, E. S., & von Hofsten, C. (2001). Predictive reaching for occluded objects by 6-month-old infants. *Journal of Cognition and Development, 2*(3), 261-281. doi:10.1207/S15327647JCD0203_2

Stedron, J. M., Sahni, S. D., & Munakata, Y. (2005). Common mechanisms for working memory and attention: The case of perseveration with visible solutions. *Journal of Cognitive Neuroscience*, *17*(4), 623-631. doi:10.1162/0898929053467622

Striano, T., & Bushnell, E. W. (2005). Haptic perception of material properties by 3-month-old infants. *Infant Behavior & Development*, *28*(3), 266-289. doi:10.1016/j.infbeh.2005.05.008

Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences*, *24*(1), 1-86. doi:10.1017/S0140525X01003910

Wada, Y., Shirai, N., Otsuka, Y., Midorikawa, A., Kanazawa, S., Dan, I., & Yamaguchi, M. K. (2009). Sound enhances detection of visual target during infancy: A study using illusory contours. *Journal of Experimental Child Psychology*, *102*(3), 315-322. doi:10.1016/j.jecp.2008.07.002

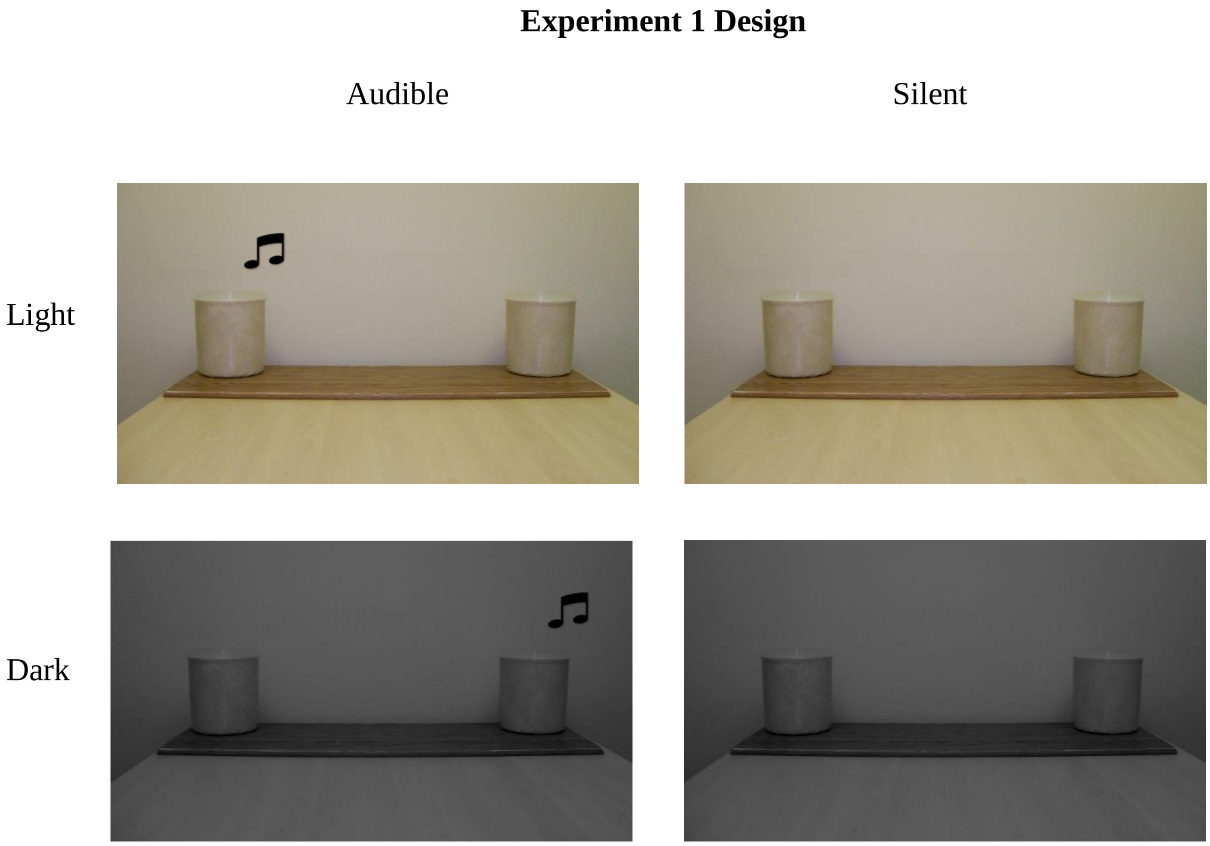
Watanabe, H., Forssman, L., Green, D., Bohlin, G., & von Hofsten, C. (2012). Attention demands influence 10- and 12-month-old infants' perseverative behavior. *Developmental Psychology*, *48*(1), 46-55. doi:10.1037/a0025412

Wilcox, T., & Smith, T. R. (2010). The development of infants' use of property-poor sounds to individuate objects. *Infant Behavior & Development*, *33*(4), 596-604. doi:10.1016/j.infbeh.2010.07.011

Wilcox, T., Woods, R., Chapa, C., & McCurry, S. (2007). Multisensory exploration and object individuation in infancy. *Developmental Psychology*, *43*(2), 479-495. doi:10.1037/0012-1649.43.2.479

Wilcox, T., Woods, R., Tuggy, L., & Napoli, R. (2006). Shake, rattle, and ... one or two objects? Young infants' use of auditory information to individuate objects. *Infancy*, *9*(1), 97-123. doi:10.1207/s15327078in0901_5

Figures



Experiment 1 Design

Figure 1. Examples of Experiment 1's A and B trials in the audible-light, audible-dark, silent-light, and silent-dark groups. The audible-light image depicts an A trial and the audible-dark image depicts a B trial. Events in the dark are depicted with shaded imaging but were completely dark from the infant’s perspective during the 5-s delay between hiding and search (recorded with infrared light).

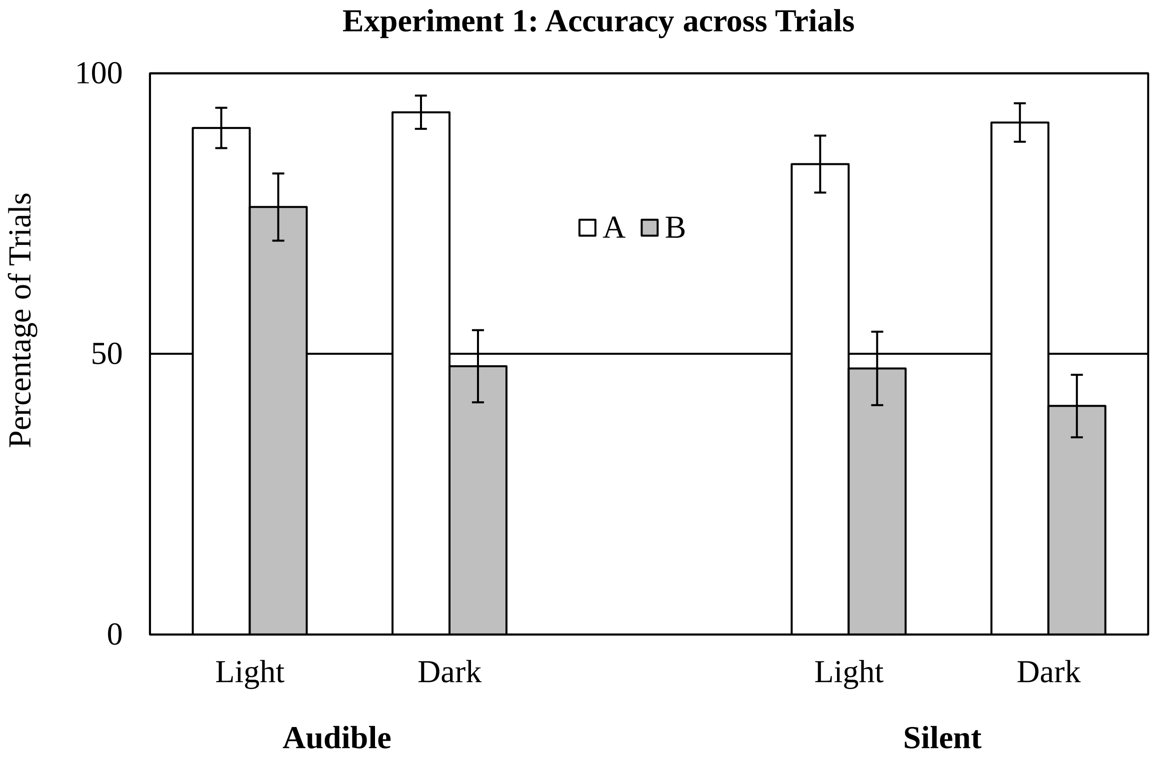


Figure 2. Percentage of A and B trials on which Experiment 1's infants searched correctly for a hidden object that was audible or silent after a delay in the light or dark. The four groups were equally successful at searching above chance (50%) at A, whereas only the audible-light group succeeded at B. Error bars in all figures reflect the standard error of the mean.

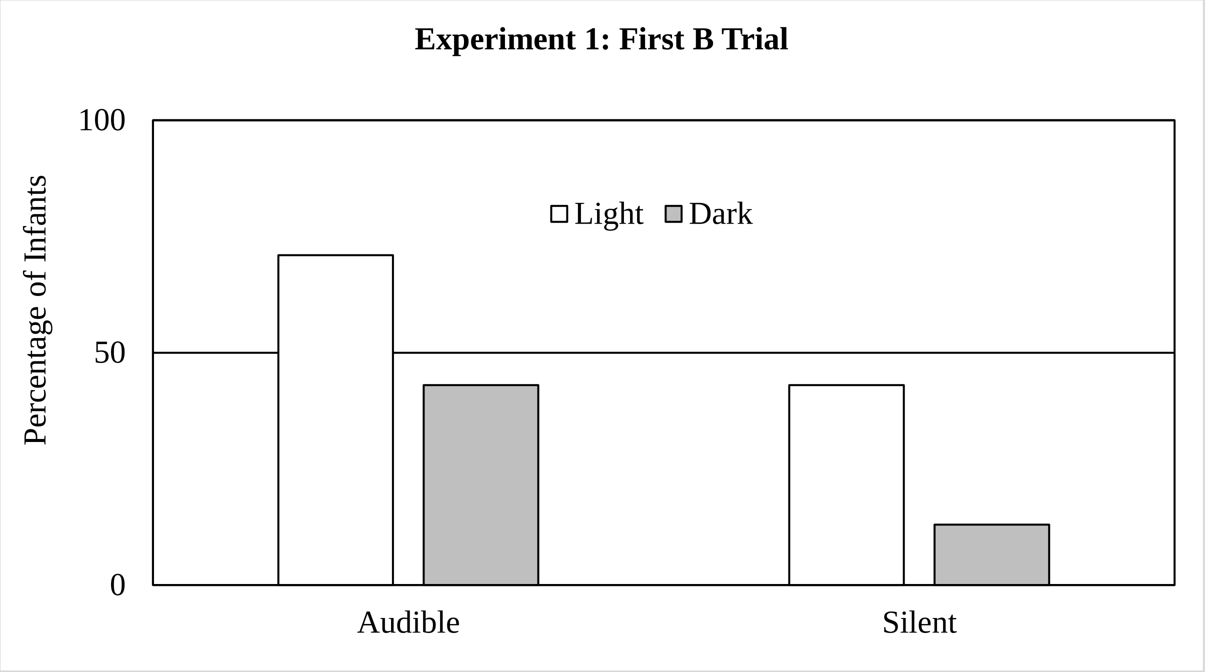


Figure 3. Percentage of Experiment 1’s infants who searched correctly on the first B trial. Infants were most likely to succeed with an audible object after a delay in the light, and least likely with a silent object after a delay in the dark.

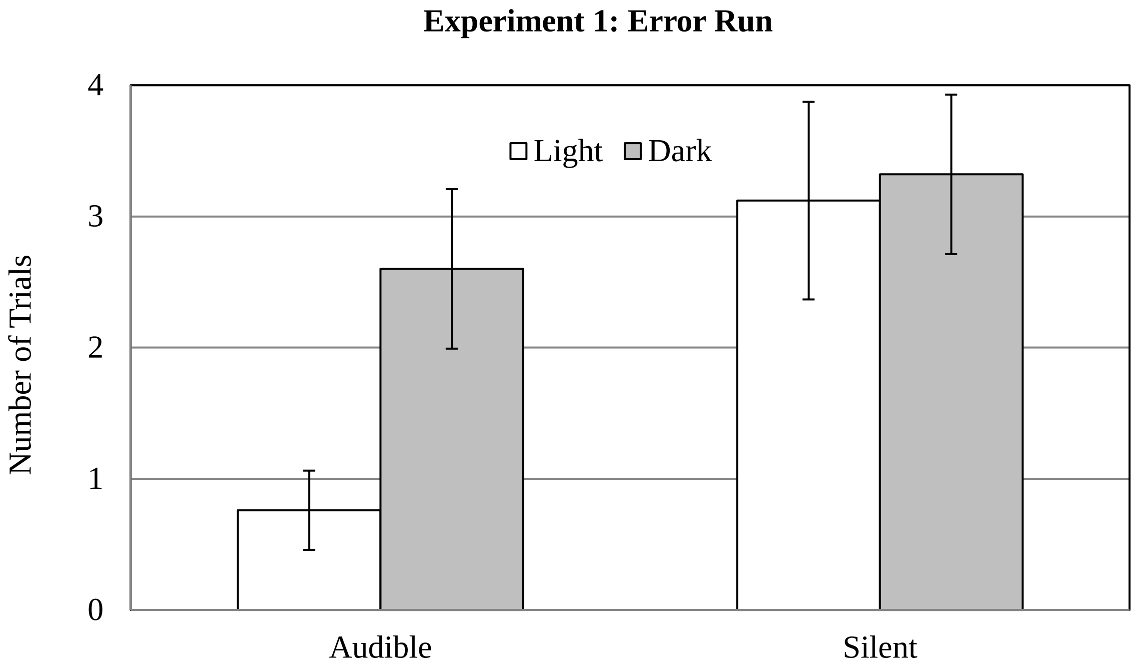


Figure 4. The number of consecutive B trials on which Experiment 1's infants erred. Infants corrected themselves in fewer trials with an audible object than a silent one, especially after a delay in the light.

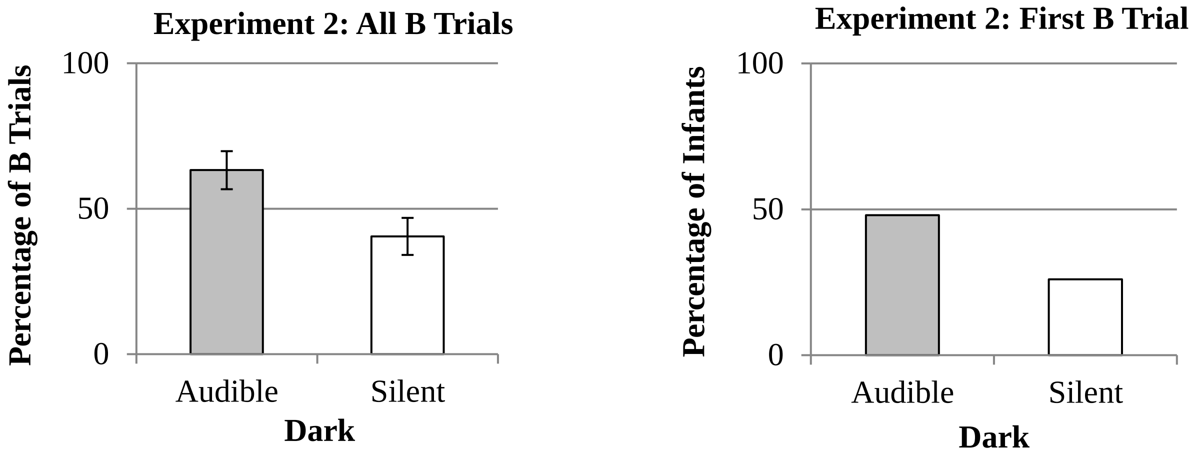


Figure 5. Percentage of B trials on which Experiment 2’s infants searched correctly for a hidden object that was audible or silent in the dark (left): Search improved to match that in the light in Experiment 1, but infants still succeeded more with audible than silent objects. Percentage of infants who searched B on the first trial (right): Search did not quite match that in the light in Experiment 1, and infants still succeeded more with audible than silent objects.

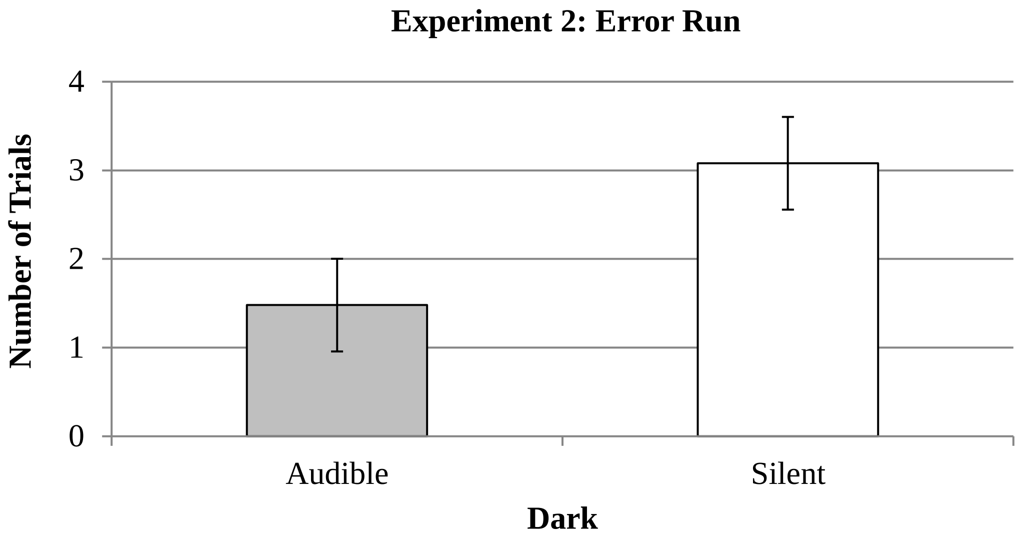


Figure 6. Number of consecutive B trials on which Experiment 2's infants erred. Error runs approximated those in the light in Experiment 1, and infants still corrected themselves in fewer trials when the object was audible than silent.