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Exploring in Silence: Hearing and Deaf Infants Explore Objects Differently before Cochlear Implantation

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Abstract

Infant development has rarely been informed by the behavior of infants with sensory differences despite increasing recognition that infant behavior itself creates sensory learning opportunities. The purpose of this study of object exploration was to compare the behavior of hearing and deaf infants, with and without cochlear implants, in order to identify the effects of profound sensorineural hearing loss on infant exploration before cochlear implantation, the behavioral effects of access to auditory feedback after cochlear implantation, and the sensory motivation for exploration behaviors performed by hearing infants as well. The results showed that 9-month-old deaf infants explored objects as often as hearing infants but they used systematically different approaches and less variation before compared to after cochlear implantation. Potential associations between these early experiences and later learning are discussed in the context of embodied developmental theory, comparative studies, and research with adults. The data call for increased recognition of the active sensorimotor nature of infant learning and future research that investigates differences in sensorimotor experience as potential mechanisms in later learning and sequential memory development.

Object exploration is a sign of infants' engagement with and motivation to learn about their world (Bradley-Johnson, Friedrich, & Wyrembelski, 1981; McCall, 1974; Ruff, Saltarelli, Capozzoli, & Dubiner, 1992; Thelen & Smith, 1994). They learn and remember more, in fact, from exploring objects themselves than from watching others act on the same objects (Daum, Prinz, & Aschersleben, 2011; Gerson & Woodward, 2014; Hayne, Barr, & Herbert, 2003; Kubicek, Jovanovic, & Schwarzer, 2017; Needham, 2009; Thelen & Smith, 1994). For example, infants who performed actions demonstrated by an experimenter recalled and reproduced those same actions six weeks later, but infants who had only observed the experimenter did not (Hayne et al., 2003). The actions that infants perform themselves and the sensorimotor feedback they generate help to form and strengthen neural connections between perceptual and motor areas in the developing brain (Kohler et al., 2002; Marshall, Young, & Meltzoff, 2011).

Hearing infants are known to systematically vary their exploration activities, creating opportunities to discover object properties and affordances, maximizing opportunities for sensory learning (Bradley-Johnson et al., 1981; Eppler, 1995; Gibson, 1988; McCall, 1974;

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Rochat, 1989; Ruff et al., 1992; Smith & Gasser, 2005; Thelen & Smith, 1994). These variations reveal both infants' motivation to learn and also *what* in particular they are interested in experiencing at a given moment. Hearing infants, for example, often explore the auditory properties of objects (McCall, 1974; Ruff, 1984) but what infants do when they cannot hear is largely unknown.

Early Exploration in Hearing Infants

In the latter part of the first year, most hearing infants routinely engage in mouthing, fingering, inspecting, shaking, and banging objects; these behaviors then decline in the second year as relational and symbolic behaviors increase (Belsky & Most, 1981; Fenson, Kagan, Kearsley, & Zelazo, 1976; Mash, Bornstein, & Banerjee, 2014; McCall, 1974; Needham, 2009; Zelazo & Kearsley, 1980). Mouthing of objects, for example, was common among 7- to 11-month-old hearing infants, occupying approximately 10 to 20% of their exploration time (McCall, 1974; Palmer, 1989), but became less frequent after 15 months of age (Belsky & Most, 1981; McCall, 1974). Individually, all infants in one study engaged in mouthing behavior (Belsky & Most, 1981) and all infants in another shook or banged objects against a table at 7 to 12 months (Thelen, 1979). Additionally, for 8- to 10-month-old infants, shaking and banging behaviors were more commonly performed with sounding objects than with non-sounding objects (Lockman & McHale; 1989; Palmer, 1989).

Infants with Profound Hearing Loss

How infants with auditory sensory differences explore objects with and without cochlear implants is unclear. It has been suggested that deaf infants (infants with profound sensorineural hearing loss, ≥ 90 dB HL) engage principally in visual exploration and that, given the absence of auditory feedback, they might explore objects less overall than hearing infants do (e.g., Koester, Papousek, & Smith-Gray, 2000; Liben, 1978; Spencer, & Deyo, 1993). However, systematic studies of their early object exploration have not been done. Moreover, in neither population (hearing or deaf) have differences in sensory feedback from object exploration been discussed in conjunction with potential implications for broader aspects of learning, information processing (e.g., visual-spatial or auditory-temporal languages) or memory. If deaf infants do focus primarily on visual exploration, for example, it is unclear why they later show smaller visual sequential memory span scores compared to hearing children and adults (e.g., AuBuchon, Pisoni, & Kronenberger, 2015).

Many deaf individuals in the United States who currently use cochlear implants—neuro-prosthetic devices that provide the sensation of hearing—received their cochlear implants between 2 and 6 years of age, and later. However, cochlear implantation began to occur at younger ages after 2000 in conjunction with changes in Food and Drug Administration guidelines that supported cochlear implantation at 12 months of age (U. S. Department of Health and Human Services, National Institutes of Health, National Institute on Deafness and Other Communication Disorders, 2011). Although today many children continue to receive cochlear implants during the preschool years, earlier implantation now permits investigating changes in infant behavior in relation to cochlear implantation. Identifying the exploration behaviors of deaf infants with and without cochlear implants is a step toward understanding their early action-perception focus and potential implications for later learning and development.

Sensory Motivation

The perceptual feedback that motivates infant actions is sometimes unclear even in hearing infants. For example, whereas hearing infants frequently shake and bang objects (McCall, 1974; Ruff, 1984), the rhythmic motor organization of these behaviors, rather than their auditory consequences, has often been examined in the past (Kahrs, Jung, & Lockman, 2103; Thelen, 1981). Clarifying the sensory motivation for these and other common early exploration behaviors is challenging, however, given that most behavior generates multimodal feedback (Gibson, 1988; Meltzoff & Borton, 1979; Rakison & Woodward, 2008; Thelen, 1979), feedback that provides redundant sensory information available across two or more senses simultaneously, and modality-specific information available to a single sense (Bahrick & Lickliter, 2014).

To temporarily limit multimodal exploration, Gibson and Walker (1984) briefly constrained 12-month-old infants' ability to access the visual modality during a study of object manipulation in the dark. After selective familiarization with rigid or soft objects, infants preferentially looked to objects with the familiarized affordance (rigid vs. soft), regardless of whether familiarization had taken place in the dark or in a lighted room. Despite this finding, infants in the study engaged in less varied object exploration in the dark than in the light; however, methods for coding exploration in each condition also differed.

Studying object manipulation in infants who have experienced limits on multimodal exploration for twelve months or more will further our understanding of how multimodal sensory feedback influences exploration overall. That is, controlling the influence of auditory perception and its effects on behavior by studying deaf infants presents a unique opportunity to identify the sensory experiences prioritized by deaf infants before cochlear implantation, the distinct behavioral effects of access to sound through cochlear implants (see also Corina & Singleton, 2009), and the sensory motivation for common infant exploration behaviors (e.g., shaking, visual inspection, etc.).

Current Study

This goal of this study of deaf and hearing infants was to test infants with profound hearing loss during the well-documented period of object exploration in the first year between 9 and 12 months (before cochlear implantation), and then to observe the relatively immediate behavioral effects of access to auditory feedback approximately four months after cochlear implant activation, in comparison to hearing peers. To our knowledge, this study is the first to examine object exploration in this way.

An earlier study of hearing infants (Gibson & Walker, 1984) temporarily limited access to visual input and found reduced variation in exploration; however, exploration duration was not reported. Therefore, in this study, reduced variation was predicted before cochlear implantation, in comparison to hearing infants, with increased variation in exploration following access to auditory feedback after cochlear implantation (e.g., Eppler, 1995;

Gibson & Walker, 1984; Gliga, 2018). Evidence from comparing hearing and deaf infants is expected to support a role for auditory feedback in repetitive shaking and banging behaviors (see also Fagan, 2015), and to identify the behaviors less likely to vary with access to auditory feedback (e.g., inspection). Studying infants with differing sensory experiences is important for understanding learning and developmental processes across populations and to inform developmental theory more inclusively.

Method

Participants

Forty-three infants participated in the study, 27 hearing infants, and 16 infants with bilateral profound sensorineural hearing loss. Each infant participated at one of two time points (Time 1, or Time 2), with a subset participating at both time points (Time 1 and Time 2; n = 8 hearing, n = 6 deaf). Table 1 shows the number of participants tested at Time 1 and/or Time 2 and the total number of sessions overall. Due to the difficulty of recruiting the relatively small population of infants with profound hearing loss and early cochlear implantation, testing infants at one or both time points in this mixed cross-sectional and longitudinal study allowed 57 data collection points in all.

All infants with profound hearing loss at Time 1 had been identified by medical providers as candidates for cochlear implant surgery, had received little to no benefit from hearing aid use, and were expected to receive cochlear implants within a few months. Infants with profound hearing loss at Time 2 all were cochlear implant users. Because the study was limited by funding timelines and surgery schedules, some infants with hearing loss had not received cochlear implants by the end of the study and so were seen only at Time 1 (n = 3; Table 1), and some were identified only after they had received cochlear implants (n = 5; Fagan, 2014) and so were tested only at Time 2. Thus, Time 1 and Time 2 are terms used to represent infant age (discussed below) and cochlear implant status (i.e., pre vs. post, respectively); however, they represent longitudinal data collection only for 14 of the 43 participants.

Time 1 participants were 15 hearing infants (H1), and 11 infants with profound sensorineural hearing loss, who had not yet received cochlear implants (Pre-CI). The mean age of infants at Time 1 was 9.9 months (SD = 1.3). Table 2 shows participants' mean age by group and time. The non-significant difference in deaf and hearing infants' ages at Time 1 (p = .49) reflects the small difference in number of participants per group (11 vs. 15).

Participants at Time 2 were 18 hearing infants (H2), and 13 infants with cochlear implants (Post-CI). Mean age at Time 2 was 17.7 months (SD = 2.9). Time 2 was designed to test Post-CI infants who had receive their cochlear implants at an early age ($M_{\text{age at implantation}}$ = 12.9 months, SD = 2.3) and who had used their implants for a relatively short period of time. Mean age at cochlear implant activation (about 6 weeks after surgery) was 14.0 months (SD = 2.2); mean duration of implant use at Time 2 was 4.2 months (SD = 2.6). Testing infants, on average, 4.2 months after implant activation allowed maximal inclusion of known infants with cochlear implants (n = 13), and observation of the relatively immediate effects of access to auditory feedback on infant behavior.

All infants (hearing and deaf) were born to hearing parents who used primarily spoken language with their children before and following cochlear implantation. At Time 1, none of the Pre-CI infants used words or signs and only one of the hearing (H1) infants used a single spoken word. All infants scored within the average range (M = 101, SD = 8.3) on the motor development subtest of the *Vineland Adaptive Behavior Scales*, Second Edition (Sparrow, Cicchetti, & Balla, 2005), administered during their first study visit. Mothers reported no developmental concerns other than hearing loss. Education level (in years) for mothers of hearing and deaf infants was 14.8 (SD = 2.8) and 14.3 years (SD = 2.9), respectively. Thirty-three infants were Caucasian, 6 were African-American, and 4 were biracial. The study was conducted according to guidelines in the Declaration of Helsinki, with written informed consent for each child obtained from a parent before any assessment or data collection. All procedures involving human subjects were approved by the Institutional Review Board at Indiana University and the University of Missouri.

Materials

Two sets of 10 objects appropriate for infant manipulation were selected to be interesting, age-appropriate, easily grasped and manipulated, and varied in their visual, tactile, and auditory characteristics or affordances. The objects were similar in type to those used in other studies of infant exploration (e.g., bells, rattles) across the first and second years (e.g., 6 to 24 months; Belsky & Most, 1981; Fagan & Iverson, 2007; Fenson et al., 1986; McCall, 1974; Palmer, 1989). Compared to other studies, however, the number and types of objects were increased (i.e., 20 objects) in order to include systematic within-set variations in shape, size, texture, hardness, appearance, moving parts, and noisemaking potential (e.g., rattle, wand of glitter), and to have enough objects to form two sets for testing across two table surfaces.

Objects in each set are pictured in Figures 1 and 1B. Clockwise, beginning at the 12 o’clock position of each figure (i.e., call bells, with and without clapper; ring of bells, with and without pellets), object appearance and shape can be compared across sets. The objects in each set were chosen to present similar affordances and to contain some differences in appearance across sets to maintain infant attention. For example, Set 1 (Fig. 1A, 3 o’clock position) contained a wood bug with moveable parts (beads and disks), and Set 2 (Fig. 1B, 3 o’clock position) contained a wooden ring with moveable trains and beads. Two objects that did not vary in shape or color/appearance across sets was a pair of wooden rings covered in plain, untextured, taupe-colored fabric (Fig. 1, 6 o’clock position in each set). These plain objects (one placed in each set) were created for comparison purposes to be the least visually, texturally, or auditorily interesting. Each object set contained two additional objects (not pictured), selected to elicit gesture use (e.g., comb), not analyzed here.

Among the objects in each set were three noisy-silent object pairs per set, similar in appearance within each pair. However, one object in each of the pairs was designed to readily produce noise when handled (e.g., bell with clapper), the other was altered so that it did not (e.g., bell with clapper removed). These six noisy-silent pairs were designed to test infants’ interest in sound-making affordances (among other affordances). Although many objects, including the silent bells might be used to make noise when banged against the hard table surface, the noisy-silent object pairs allowed systematic comparisons of within-pair manipulation. In addition to documenting exploration within the noisy-silent pairs, however, eight target behaviors (described below) were documented across all objects.

Procedure

Infants were videotaped seated on the lap of a caregiver in front of a table. Infants were tested using routine procedures (e.g., Gibson & Walker, 1984; Palmer, 1989), while maximizing opportunities for object exploration by increasing both the number and types of objects infants could explore. The examiner, seated across the table from the infant, presented each object at midline, one object at a time. Infants could freely explore and manipulate each object for 30 s, beginning when the object was first touched. After 30 s elapsed, the object was retrieved by the examiner and another object was offered. Each 30 s period was monitored by the examiner using a stopwatch held under the table. To further vary sound exploration opportunities, a foam mat (1” thick) was placed on the table for presentation of one object set; the table surface was bare for the other set. Order of object set and table surface were counter balanced; objects within sets were presented in random order.

Coding

Eight object exploration categories, commonly coded in other studies of exploration (Gibson & Walker, 1984; Lockman & McHale, 1989; McCall, 1974; Palmer, 1989; Rochat, 1989; Ruff, 1984, 1986; Ruff et al., 1992) were identified from the video record as follows.

Finger: move fingers along the surface of an object or object part

Inspect: hold and visually inspect object for ≥ 1 s

Mouth: put object in mouth or touch object to lips or tongue

Pat: pat object with hand, or tap it against the hand

Shake/Bang: move object up-and-down or side-to-side in midair, or bang it against another surface

Slide: move object back-and-forth or side-to-side along the table surface

Throw: throw, toss, or release object by opening the hand to let it fall

Other: After coding all actions individually, the four least frequently occurring actions were grouped together in this category for data analysis. The mean proportion of exploration duration for these behaviors, in combination, was only .01 (*SD* = .02). The four infrequent actions were: flick—contract and extend fingers against an object (mean instances per participant = 0.21); press—press or squeeze object (mean instances = 1.25); pull—pull on object with fingers (mean instances = 0.11); and turn—spin or turn a moving object part (e.g., a bead; mean instances = 0.28).

The eight exploration behaviors were coded from the videotape record. Coding of the exploration behaviors for a given object began when the infant first touched the object (with either or both hands) and ended 30 seconds after the first touch. The beginning and end time for each observed behavior was documented using the time clock on the video record for calculation of exploration duration for each behavior and with each object.

Additionally, number of instances per behavior (per object) was also documented, as was the number of complete cycles for shake/bang and slide behaviors. Brief interruptions in an ongoing behavior (≤ 1s) were considered part of one occurrence (e.g., infant removed object from mouth for <1 s then resumed mouthing). Behaviors interrupted for >1s were coded as separate instances of a given behavior. Holding an object only—without movement, manipulation, or visual inspection—was not coded, nor was looking toward an object when it was not being held, touched, or manipulated.

Reliability

Four graduate and undergraduate students trained on the coding categories identified and classified all exploration behaviors (type, duration, number of instances). To assess reliability, 11 randomly selected videotape records (19%) were independently coded in full by a second coder. The intra-class correlation coefficient (ICC) for the number of behaviors instances identified from these records was .921. The ICC for duration of behaviors identified was .95. Point by point percent agreement for classification of exploration type was 86.2%.

Statistical Analysis

To address both duration and type of object manipulation, the dependent variables were exploration duration, and number of occurrences of each identified behavior type above. Because some infants contributed data to both time points (Table 1), data for each time point were analyzed separately, using independent- or paired-samples *t*-tests and repeated-measures Analysis of Variance (ANOVA). Because group sizes at each time point were relatively small, paired comparisons were minimized and alpha levels were uncorrected; however, effect sizes were also calculated and included. Arcsine transformations were used in all proportional data analysis (proportion of total exploration duration).

Results

Preliminary analyses showed that overall exploration duration did not differ significantly by object set, paired-samples $t(56) = .77$, $p = .44$; table surface, $t(56) = .60$, $p = .55$; order of set presentation, independent-samples $t(55) = 1.73$, $p = .08$; or gender, independent-samples $t(41) = 1.56$, $p = .13$.

Duration by Object Type

A repeated-measures ANOVA across all participants, indicated a significant difference in exploration duration among objects, $F(9, 504) = 32.47$, $p < .001$, $\eta_p^2 = .371$. Planned contrasts indicated that infants manipulated the taupe rings (created to be the least visually, texturally, or auditorily interesting) for less time on average than any of the other objects (all $p < .01$), except the baseball/soccer rattles, $F(1, 56) = 1.74$, $p = .192$. Yet infants manipulate even these plain taupe rings for about one-third of the 30 s time allotted per object (10.45 s).

Table 3 lists the average exploration time (in seconds) for objects within each pair and the overall mean (16.13 s).

Total Exploration Duration

Together, deaf and hearing infants explored objects for more than half the 600-second period (i.e., 10 minutes) allotted (M = 322.6 s, SD = 73.7). Independent-samples t-tests indicated no significant differences in overall exploration duration between groups at Time 1 (Pre-CI vs. H1), $t(24) = .49$, $p = .62$, or Time 2 (CI vs. H2), $t(29) = .35$, $p = .72$, and no differences in mean duration per object at either time point, Time 1, $t(517) = 1.09$, $p = .28$, or Time 2, $t(618) = .66$, $p > .50$. Thus, profound hearing loss did not affect infants' overall motivation to explore or their attention to individual objects. Figure 2 shows overall exploration duration and duration per object by group and time.

Time 1 Exploration Behavior Types: Variation and Duration

Variation.—At Time 1, however, object exploration was significantly less varied in infants with hearing loss compared to their hearing peers. On average, the Pre-CI infants engaged in a mean of 6.6 (SD = 1.20) different exploratory behavior types overall, whereas hearing infants (H1) engaged in 8.0 (SD = .92), $t(24) = 3.26$, $p < .01$, $d = 1.27$. Figure 3 shows the mean number of different exploration behavior types for each group.

Duration proportions.—A Time 1 group (H1, Pre-CI) x behavior (8 behaviors) repeated measures ANOVA indicated a significant group x behavior interaction, $F(7, 168) = 3.61$, $p < .01$, $\eta_p^2 = .13$, with follow-up analyses showing Pre-CI infants differed significantly from hearing infants in two ways. First, Pre-CI infants spent nearly twice as much time, proportionally, exploring objects by mouthing as H1 infants did, 0.39 vs. 0.22), $t(24) = 2.40$, $p < .05$, $d = .92$. The second principal difference was that object shaking and banging occurred for a significantly smaller proportion of total exploration time in the Pre-CI than the H1 group, $t(24) = 2.22$, $p < .05$, $d = 0.94$. Figure 4 shows proportion of total exploration duration per behavior by group and time. Moreover, Pre-CI infants explored fewer than half as many objects by shaking (2.8 vs. 6.2), $t(24) = 2.88$, $p < .01$, $d = 1.14$, and their latency to first shake per object was more than twice as long as H1 infants' (18.21 s vs. 9.05 s), $t(24) = 3.31$, $p < .01$, $d = 1.25$.

Time 2 Exploration Behavior Types: Variation and Duration

Variation.—Post-CI and H2 infants engaged in similar numbers of different exploration behaviors overall at Time 2 (M =7.9, SD = 1.1, and M = 7.8, SD = 1.3, respectively), $t(29) = 0.07$, $p = .94$.

Duration proportions.—For infants at Time 2, the group x behavior repeated measures ANOVA interaction was no longer significant, $F(7, 203) = 0.95$, $p = .46$, $\eta_p^2 = .03$. However, the main effect of behavior was significant, $F(7, 203) = 61.82$, $p < .001$, $\eta_p^2 = .68$; planned contrasts showed inspection proportions exceeded all other behavior proportions (all $p < .001$), except fingering ($p = .58$). The main effect of group was not significant, $F(1, 29) = 0.84$, $p = .36$, $\eta_p^2 = .02$. Thus, the Post-CI and H2 groups did not differ significantly for proportion of object shake/bang behaviors, $t(29) = 1.41$, $p = .57$, $d = 0.17$, or for proportion of mouthing exploration behavior, $t(29) = 1.53$, $p = .18$. Mouthing in Post-CI infants was nearly one-fourth the level of Pre-CI infants' ($M = 0.11$ vs. 0.39; Fig. 4).

Thus, Post-CI exploration was both similar in behavior type and as varied as H2 hearing peers' only four months after infants with profound hearing loss received cochlear implants. In neither age group (Time 1 or Time 2) did infants with hearing loss (Pre- or Post-CI) visually inspect objects more than their hearing peers (Fig. 4), Pre-CI versus H1, $t(24) = 0.23$, $p = .81$; Post-CI versus H2, $t(29) = 0.22$, $p = .82$, nor did they show a significant preference, proportionally, for visual inspection over other forms of exploration. For example, inspection and fingering proportions did not significantly differ between groups at either Time 1 or Time 2. For both groups (hearing and deaf), fingering proportions were larger at Time 2 compared with Time 1, but they did not differ significantly within each time point.

Descriptive Analysis of Longitudinal Data:

Statistical analyses were not performed across time points because the Time 1 and Time 2 data sets were not independent (see method section). However, for descriptive comparison purposes, Figure 5 shows proportions of total duration for each exploration type only for those infants who were tested at both time points (i.e., $n = 6$ hearing, and $n = 8$ deaf infants; Table 1). Although the number of participants in each group with data at both time points was small, Fig. 5 shows exploration patterns roughly similar to those in Fig. 4 for the full data set. For example, from Pre- to Post-CI, shake/bang duration proportions nearly doubled (.07 to .14, respectively) in this small group ($n = 8$).

Noisy/Silent Object Pairs

A final set of analyses examined differential exploration duration within the six noisy/silent object pairs only. Across all groups, infants manipulated the noisy ($M = 16.6$ s, $SD = 7.3$) and silent ($M = 16.1$ s, $SD = 7.2$) objects in these pairs for a similar amount of time (in seconds) overall, paired-samples $t(341) = 1.24$, $p = .21$. However, at Time 1, a group (hearing, deaf) x object type (noisy, silent) repeated measures ANOVA indicated a significant group x object interaction, $F(1, 24) = 5.20$, $p < .05$, $\eta_p^2 = .17$, for shake duration. Paired-samples t-tests showed H1 infants spent more time shaking the noisy objects than the silent objects, $t(14) = 2.47$, $p < .05$, $d = 0.89$; Pre-CI infants did not ($p = .34$).

The group x object type interaction was no longer significant at Time 2, $F(1, 29) = 0.007$, $p = .93$, $\eta_p^2 = .00$. The main effect of group was also not significant, $F(1, 29) = 0.44$, $p = .50$, $\eta_p^2 = .01$. However, there was a significant main effect of object type, $F(1, 29) = 9.07$, $p < .01$, $\eta_p^2 = .23$. Across groups (Post-CI and H2, combined), infants shook noisy objects longer than silent objects ($M = 3.2$ vs. 2.81 s, respectively). However, whereas H2 infants spent significantly more time shaking the noisy objects than the silent objects, $t(17) = 2.40$, $p < .05$, $d = 0.76$, Post-CI infants showed a marginally significant difference in the same direction, $t(12) = 1.90$, $p = .08$, $d = 0.67$. Figure 6 shows mean shake duration (in seconds) for the noisy-silent object pairs by group and time.

Discussion

Studying hearing and deaf infants together uncovered new evidence of associations between sensory perception and early behavior, revealed the sensory experience prioritized by infants with profound hearing loss during object exploration, and clarified the sensory motivation for exploratory behaviors commonly performed by hearing infants as well. The data showed, foremost, that profound hearing loss did not diminish infants' motivation to explore objects. In terms of overall duration, they generated as much exploration activity as hearing infants did, regardless of the absence of auditory sensation. By robustly exploring objects themselves, they created opportunities for learning and multimodal feedback from non-auditory modalities before cochlear implantation and from both auditory and non-auditory modalities after cochlear implantation.

However, compared to hearing infants of the same age, Pre-CI infants' exploration was less varied and differed in emphasis in two ways. First, Pre-CI infants maximized sensory experience by mouthing objects significantly more than hearing infants did. By prioritizing mouthing exploration for nearly 40% of total exploration time—twice the duration demonstrated by the hearing infants in this study and others (McCall, 1974; Palmer, 1989)—Pre-CI infants selectively focused on a feedback mechanism known to facilitate cross-modal learning about shape, size, and texture in hearing infants (Fagan & Iverson, 2007; Gibson & Walker, 1984; Meltzoff & Borton, 1979). After cochlear implantation, however, remarkably little time was devoted to mouthing by either group (Post-CI or H2; 6–11%), consistent with the decline in mouthing found in studies of hearing infants in the second year (Belsky & Most, 1981). If the Post-CI decline in mouthing in infants with cochlear implants could be wholly attributable to age, rather than to the effects of cochlear implantation, then differences in mouthing between 9-month-old hearing and deaf infants at Time 1 should not have occurred. That is, whereas 9-month-old hearing infants showed mouthing proportions similar to those documented in other studies of hearing infants in the first year (Belsky & Most, 1981; McCall, 1974; Palmer, 1989), only 9-month-old infants who could not hear (Pre-CI) overwhelmingly prioritized mouthing at Time 1.

Second, compared to their hearing peers, deaf infants spent less time shaking and banging objects before, but not after cochlear implantation, highlighting both a substantial role for auditory feedback in motivating these behaviors previously noted primarily for their repetitive cyclic organization alone, and infants' new interest in generating auditory feedback soon after they could hear it. Interest in generating auditory feedback in repetition and vocalization has also been documented soon after cochlear implantation (Fagan, 2014, 2015). Gliga (2018) and Eppler (1995) have argued, respectively, that increased motor activity and variability represent active learning, and that increased attention to auditory and visual object properties guides new actions. The increased variability (exploration types) and selective motor activity (shaking and banging) observed in this study, therefore, suggest periods of active learning and auditory attention with cochlear implants.

Although Palmer (1989) did not report duration, she also noted 9-month-old hearing infants' interest in shaking and banging objects (i.e., 2–16 times per object); infants shook sounding objects more frequently than silent objects, consistent with the behavior of hearing infants at

Time 1 in this study. Post-CI infants' behavior with the noisy-silent object pairs suggests they too were beginning to differentiate, selectively act on, and perhaps test hypotheses about auditory affordances (Eppler, 1995; Gliga, 2018; Mash et al., 2014).

The systematic differences in sensorimotor behavior evident in these exploration patterns extend and reveal anew the dynamic and reciprocal nature of early action-perception relationships. They show that infants actively and adaptively chose voluntary motor activities that generated sensory experiences they could perceive and control, in keeping with embodied, dynamic systems theories of development (Thelen & Smith, 1994). As Overton (2015) proposed, infants behaved and experienced the world not only as agents with a particular kind of body—but also as agents with particular sensory resources. When sound was inaccessible, 9-month-old Pre-CI infants flexibly adapted object manipulation to maximize sensory feedback from mouthing and other exploration behaviors. They engaged in behaviors typical for their age group (Belsky & Most, 1981; Fenson et al., 1976; McCall, 1974; Palmer, 1989; Thelen, 1979; Zelazo & Kearsley, 1980) but in proportions redistributed to accommodate and exploit feedback they could perceive. Contrary to some beliefs, however, there was no evidence to suggest they were visual learners primarily, or that they engaged in visual exploration more than their hearing peers, Pre- or Post-CI.

Efforts to explain exactly how infant behavior shapes learning and cognitive development are growing (Gliga, 2018; Marshall, 2016; Rakison & Woodward, 2008; Smith & Gasser, 2005; Tamis-LeMonda, Kuchirko, & Tafuro, 2013; Woodward & Needham, 2009). In experimental tasks with hearing infants, for instance, active object manipulation experience influenced word learning and neurocognitive representations, understanding of intention (Gerson & Woodward, 2014; Kannass & Oakes, 2008; Thelen & Smith, 1994; Yee, Chrysikou, Hoffman, & Thompson-Schill, 2013; Yu & Smith, 2012), and memory reactivation and generalization (Bahrick & Lickliter, 2014; Bauer, 2009; Hayne et al., 2003; Rovee-Collier, Hartshorn, & DiRubbo, 1999). The differing object exploration experiences of infants with profound hearing loss, therefore, are likely to shape learning, memory, and cognitive development in different ways.

More research is needed to investigate this possibility, perhaps by examining potential associations between spatial experience with objects and the established shape bias in object categorization (Samuelson & Smith, 2000), and between spatial and auditory experience with objects and visual and auditory sequential memory. The persistently short visual and auditory sequential memory spans of children with long-term cochlear implant experience is well established (AuBuchon et al., 2015; Conway, Pisoni, & Kronenberger, 2009; Fagan, Pisoni, Horn, & Dillon, 2007; Pisoni, Kronenberger, Chandramouli, & Conway, 2016), as is the short visual sequential memory span of deaf adults with sign language expertise (Boutla, Supalla, Newport, & Bavelier, 2004; Marschark, Sarchet, & Trani, 2016). Deaf adults who use American Sign Language (ASL), however, performed better than hearing individuals on synchronizing finger tapping to visual flashes (Iversen, Patel, Nicodemus, & Emmorey, 2015).

Whether or not temporally organized auditory feedback from repetitive actions with objects (e.g., shaking noisy objects), as well as early spoken language experience, influences later sequential encoding and retrieval is unclear. Torkildsen, Arciuli, Haukedal, and Wie (2018) recently found, however, that 7- to 12-year-old deaf children with cochlear implants showed *implicit* visual sequence learning comparable to that of hearing children.

Several studies of hearing adults are also relevant for questions about sequential memory and sensorimotor experience (Chemin, Mouraux, & Nozaradan, 2014; Guttman, Gilroy, & Blake, 2005; Hickok, Farahbod, & Saberi, 2015). In these studies, performing rhythmic body movements influenced adults' rhythm perception and EEG patterns in response to ambiguous music patterns (Chemin et al., 2014), and Guttman et al. (2005) found rhythmically sequenced visual patterns became automatically encoded in an auditory form. These studies could be extended to include children and adults with cochlear implants.

Comparative research also found that routine differences in environmental exploration in genetically identical mice were correlated with differences in neuronal growth in the hippocampus (Freund et al., 2013), a cortical region active in memory tasks. The mechanism proposed was that, over time, the sensory feedback from wide-ranging environmental exploration signaled the presence of cognitively challenging environments best survived by adaptive neuronal growth. In effect, normal variation in exploration resulted in neuronal variation. Similarly, relatively small differences in early exploration in deaf and hearing infants may influence neuronal growth and organization.

The current study was limited by relatively small numbers of participants, one or two data points per individual, and the absence of a non-implanted participant sample at Time 2 to test the ongoing effects of limited auditory access across infant age. An additional limitation is that sequential memory was not assessed in this study. Although, exploratory variation did increase after cochlear implantation, most sequential memory studies have included children who received cochlear implants at considerably later ages than in the present study (e.g., Fagan et al., 2007; Marschark et al., 2015; Pisoni et al., 2016). Therefore, future studies should test sequential memory outcomes in children who receive cochlear implants by 12 months of age or younger.

In summary, this study has shown that infants with profound sensorineural hearing loss explore objects differently than hearing infants before, but not after cochlear implantation. In new ways, the results demonstrate the influence of sensory feedback on object exploration and the effects of limited feedback from the auditory modality on variation specifically. The results extend evidence of decreased variation in object exploration under conditions of briefly limited access to the visual modality (Gibson & Walker, 1984) to more enduring limitations in access to the auditory modality. Despite the fact that, in most respects, Post-CI exploration patterns in this study appeared to match hearing peers', the young 17-month-old Post-CI infants had at that time only a few months of experience with the timing and rhythm of the auditory consequences of their actions, whereas their hearing peers had nearly 18 months of auditory experience. There is much still to be done to understand the potential effects of these early differences in auditory experience on later learning and memory.

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Figure 1.
Objects in object set 1 (A) and object set 2 (B).

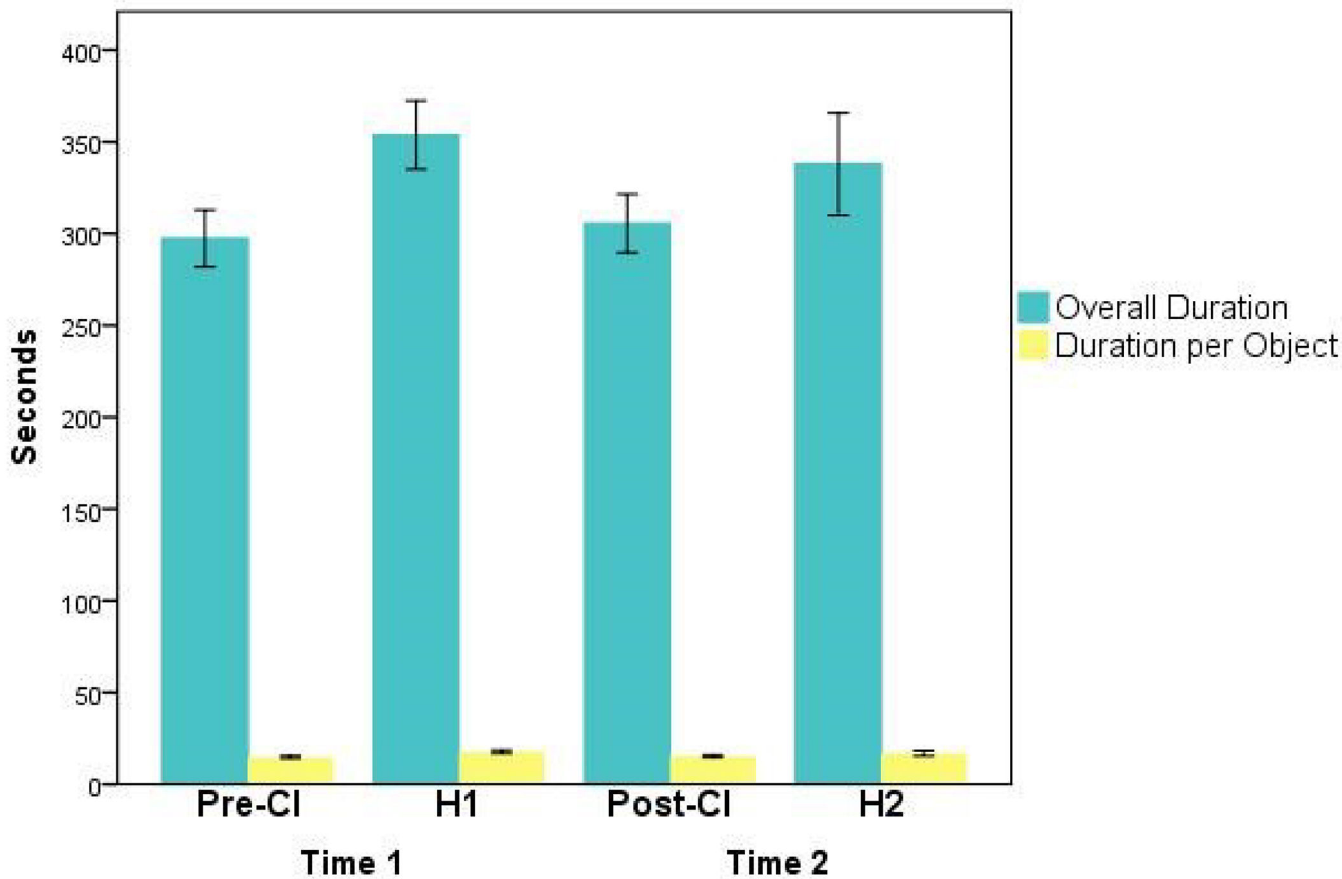

Figure 2.
Mean overall duration of object manipulation and duration per object by group and time. Pre-CI = before cochlear implantation (n = 11); H1 = hearing infants at Time 1(n = 15); Post-CI = after cochlear implantation (n = 13); H2 = hearing infants at Time 2 (n = 18). Note. Bars represent +/− 1 standard error.

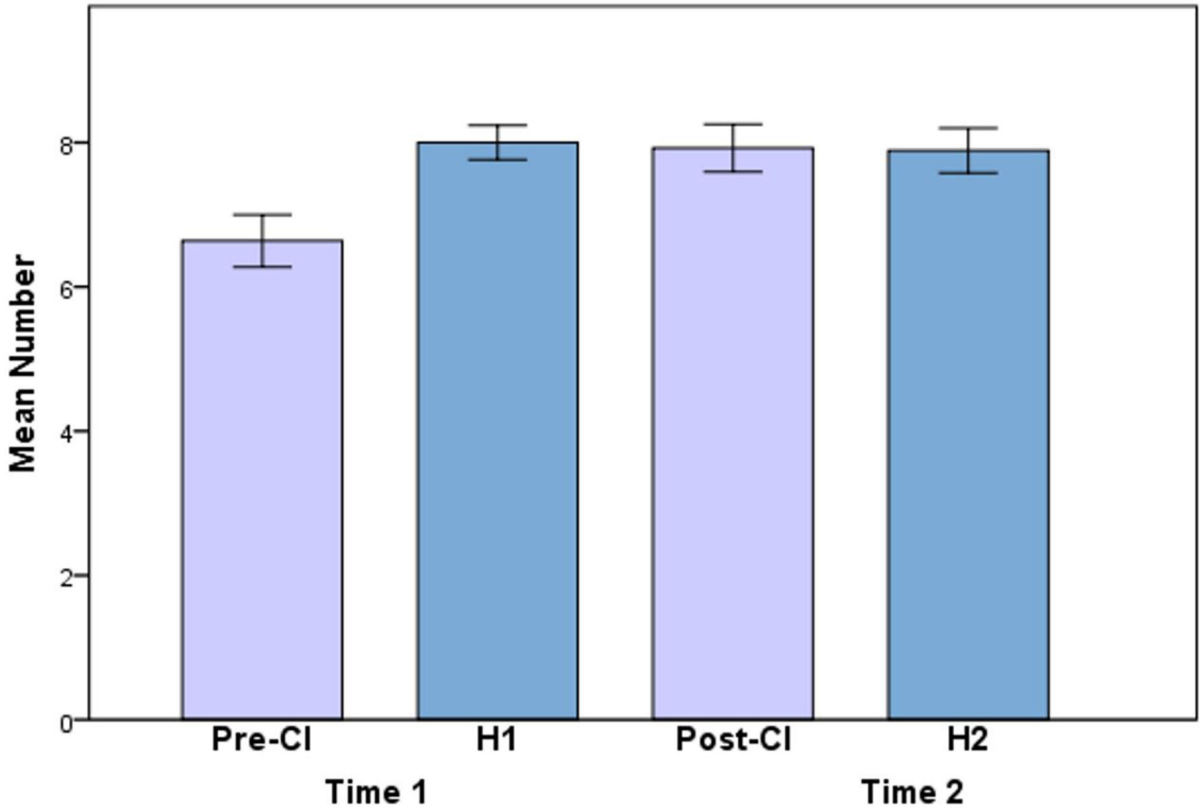

Figure 3.
Mean number of different exploration behaviors by group and time. Pre-CI = before cochlear implantation (n = 11); H1 = hearing infants at Time 1 (n = 15); Post-CI = after cochlear implantation (n = 13); H2 = hearing infants at Time 2 (n = 18). Note. Bars represent +/− 1 standard error.

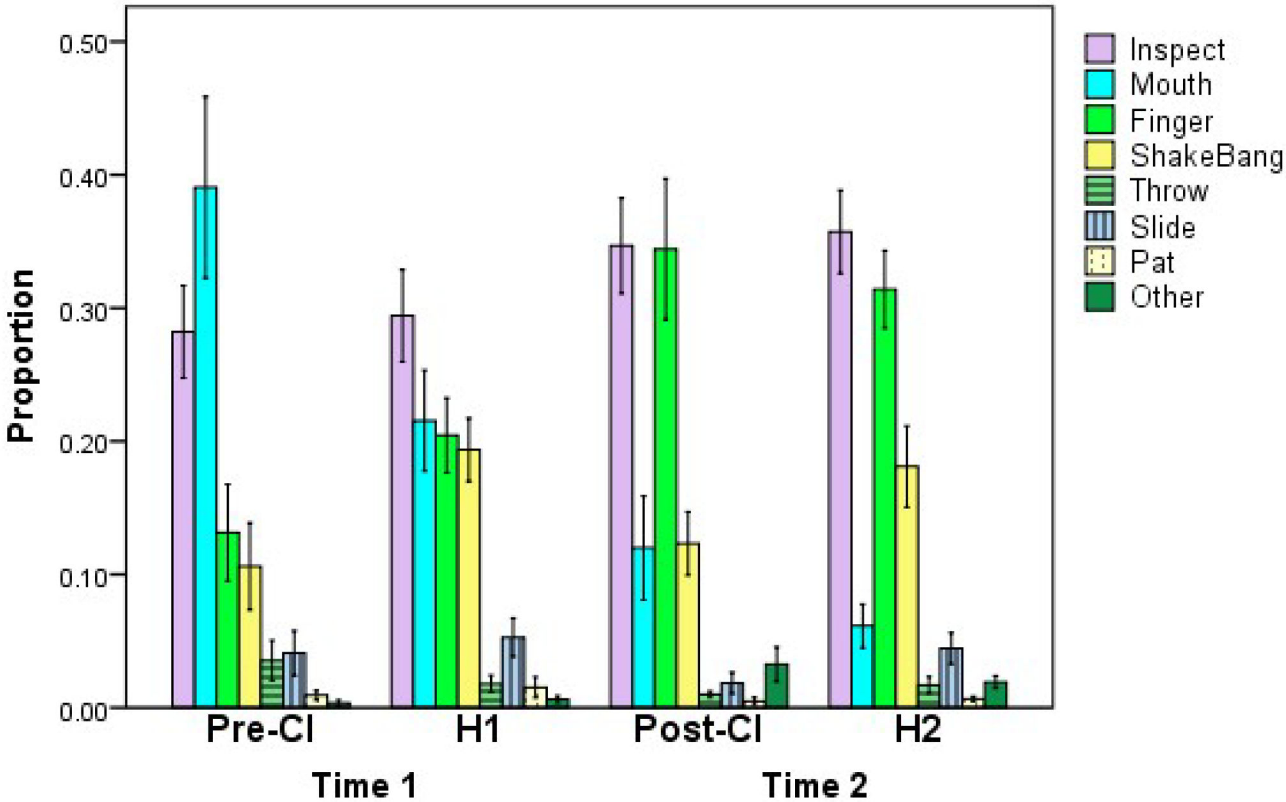

Figure 4.

Mean proportion of exploration time per behavior by group and time. Pre-CI = before cochlear implantation (n = 11); H1 = hearing infants at Time 1 (n = 15); Post-CI = after cochlear implantation (n = 13); H2 = hearing infants at Time 2 (n = 18). Note. Bars represent +/− 1 standard error.

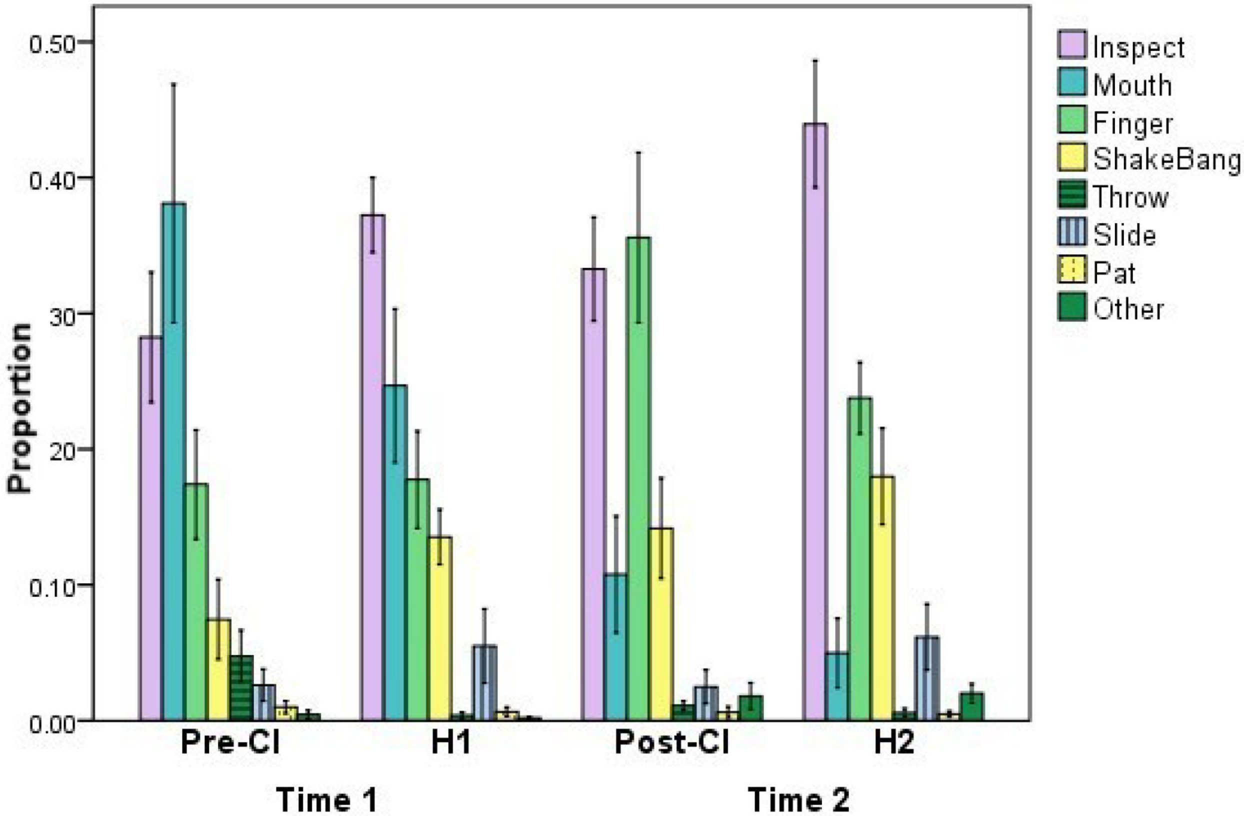

Figure 5.

Mean proportions of exploration duration per behavior only for those infants who were tested at both time points. Pre-CI = before cochlear implantation (n = 8); H1 = hearing infants at Time 1 (n = 6); Post-CI = after cochlear implantation (n = 8); H2 = hearing infants at Time 2 (n = 6). Note. Bars represent +/− 1 standard error.

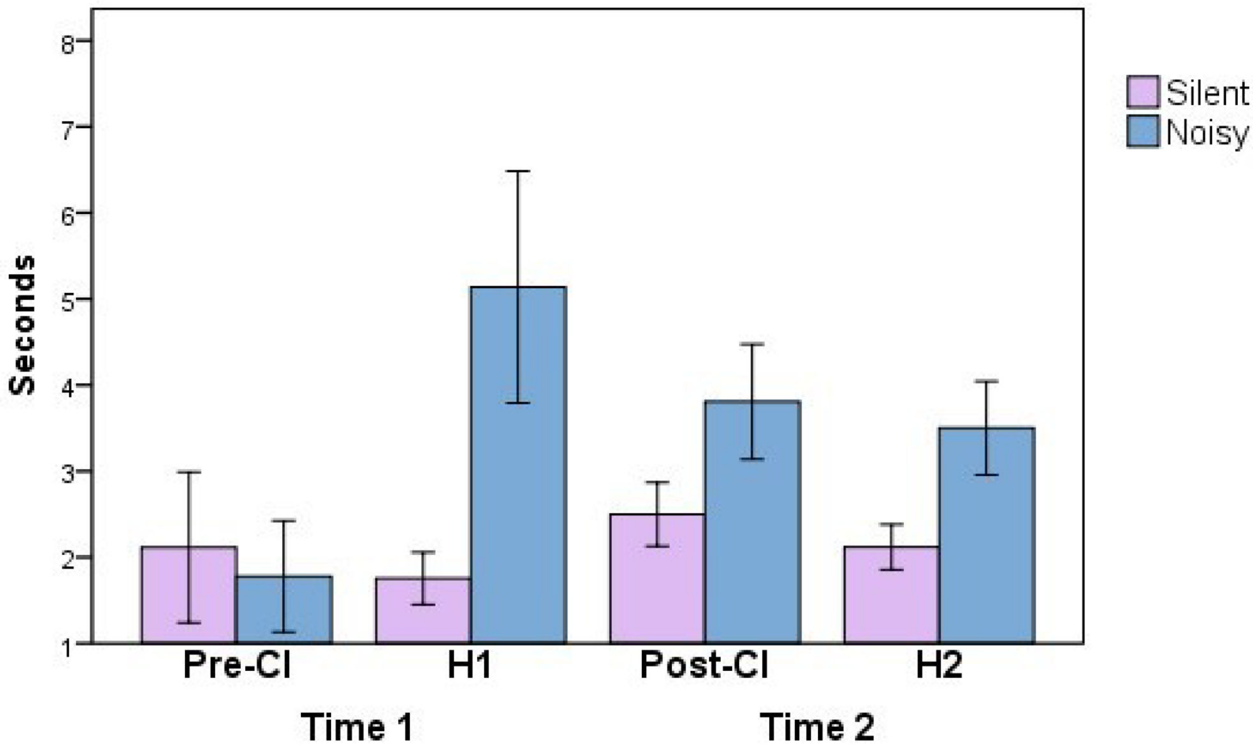

Figure 6.

Mean shake duration for silent versus noisy objects by group and time. Pre-CI = before cochlear implantation (n = 11); H1 = hearing infants at Time 1 (n = 15); Post-CI = after cochlear implantation (n = 13); H2 = hearing infants at Time 2 (n = 18). Note. Bars represent +/− 1 standard error

Table 1

Number of Participants in each Group Tested at Time 1 and/or Time 2 and Total Number of Testing Sessions

Group	Time 1 Only	Times 1 and 2	Time 2 Only	Experimental Sessions
Profound Hearing Loss (*n* = 16)	3	8	5	24
Hearing (*n* = 27)	9	6	12	33
				Total = 57

Table 2

Participants' Mean Age (in Months) by Group and Time

	Time 1		Time 2	
Measure	**Pre-CI**	**H1**	**Post-CI**	**H2**
Participants	11	15	13	18
Age by Group	10.1 (*1.3*)	9.8 (*1.4*)	18.1 (*2.6*)	17.4 (3.2)
Age by Time	9.9 (*1.3*)		17.8 (*2.9*)	

Note. Mean and (standard deviation). Within-time age differences n.s. (Time 1, $p = .49$; Time 2, $p = .45$).

Table 3

Mean (SD) Exploration Duration (in Seconds) for Objects within Object Pairs

Object Pair	**Duration**
Taupe Rings	10.45 (*7.55*)
Baseball/Soccer Rattles	11.55 (*6.99*)
Donut-shaped Rattles	13.62 (*7.26*)
Colorful Textured Rings	14.35 (*7.03*)
Jingle Bells	17.00 (*7.05*)
Green/Orange Shakers	17.66 (*5.94*)
Glitter Wands	18.57 (*6.49*)
Blue/Yellow Shakers	18.61 (*6.08*)
Wooden Bug/Trains	19.59 (*6.95*)
Call Bells	19.85 (*6.68*)
Overall Mean (*SD*):	16.13 (*7.52*)