JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 2008, **89,** 407–424 NUMBER 3 (MAY)

RELATIONAL LEARNING IN CHILDREN WITH DEAFNESS AND COCHLEAR IMPLANTS

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This four-experiment series sought to evaluate the potential of children with neurosensory deafness and cochlear implants to exhibit auditory–visual and visual–visual stimulus equivalence relations within a matching-to-sample format. Twelve children who became deaf prior to acquiring language (prelingual) and four who became deaf afterwards (postlingual) were studied. All children learned auditory–visual conditional discriminations and nearly all showed emergent equivalence relations. Naming tests, conducted with a subset of the children, showed no consistent relationship to the equivalence-test outcomes. This study makes several contributions to the literature on stimulus equivalence. First, it demonstrates that both pre- and postlingually deaf children can acquire auditory–visual equivalence relations after cochlear implantation, thus demonstrating symbolic functioning. Second, it directs attention to a population that may be especially interesting for researchers seeking to analyze the relationship between speaker and listener repertoires. Third, it demonstrates the feasibility of conducting experimental studies of stimulus control processes within the limitations of a hospital, which these children must visit routinely for the maintenance of their cochlear implants.

Key words: cochlear implant, symbolic function, stimulus equivalence, deaf children, mouse clicks

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Cochlear implants permit deaf children to detect and discriminate auditory stimuli, including spoken words. Regarding the latter especially, one important issue is the nature of auditory functions permitted by the implant (Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). For example, do these children develop auditory–visual stimulus–stimulus relations that are truly symbolic? The stimulus equivalence paradigm provides operational criteria to distinguish truly symbolic from mere conditional (''if–then'') relations (Sidman & Tailby, 1982). If, for example, a participant learns auditory–visual conditional discriminations AB and AC and subsequently shows the emergence of visual–visual relations BC and CB without explicit discrimination training, then this outcome indicates formation of equivalence classes and thus true symbolic relations (see Sidman & Tailby,1982, for a description of appropriate equivalence tests).

Children with congenital or acquired deafness comprise a unique population for experimental and clinical studies of stimulus equivalence class formation, particularly with ''cross modal'' (i.e., auditory–visual) classes. Neurosensory deafness imposes virtual absence of useful auditory stimulation, and it is thus possible to study various prerequisite and/or concurrent behavioral processes of interest in a highly controlled fashion (e.g., emergent naming under conditions of presence vs. absence of coincident cochlear implant-delivered auditory input).

Experiments 1-3 are based in part on a dissertation submitted by A. C. M. Almeida-Verdu in partial fulfillment of the requirements for a doctoral degree in Special Education, Universidade Federal de São Carlos (UFSCar). Experiment 4 is based on a thesis submitted by E. M. Huziwara in partial fulfillment of the requirements for a Master's degree in Special Education, also at UFSCar. He is now at the Universidade de São Paulo.

The research program has been supported by FAPESP/PRONEX (Grant 2003/09928-4), and by Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazilian Research Council - Grants 522290/95-7 and 479436/03-7, and fellowships). Manuscript preparation was supported in part by grants from the U. S. National Institute of Child Health and Human Development (HD39816, HD04147).

We thank Wagner R. da Silva, whose initial findings inspired this program, speech pathologist Leandra T. Nascimento for help in recruiting and selecting participants, Joanne Kledaras and Drausio Capobianco for solving some difficult problems in preparing the figures, and William Dube and Elenice Hanna for comments on the manuscript. Finally, we thank the children and their families for their participation.

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doi: 10.1901/jeab.2008-89-407

To our knowledge, the first study to evaluate the possibility of developing auditory–visual and visual–visual stimulus equivalence with this population was reported recently by da Silva, de Souza, de Rose, Lopes Jr., Bevilacqua and McIlvane (2006). The goal of their preliminary investigation was to evaluate the feasibility of conducting experimental studies of stimulus control processes (including formation of equivalence classes) in (a) 2 adolescents who acquired deafness postlingually (i.e., after language had developed) and (b) 2 children who were deaf prelingually (before development of language). Another important aspect of this preliminary study was to evaluate the feasibility of conducting formal stimulus-control research on an accelerated schedule during the course of a brief visit (typically 3 days) scheduled for implant evaluation and maintenance. Each of the 4 participants learned conditional discriminations AB and AC among visual stimuli (printed Greek letters), and showed visual–visual equivalence classes (i.e., emergent BC and CB relations). Next, auditory sample stimuli (a sequence of five 1-s discrete pulses, Set D) were introduced via direct electrical stimulation of the cochlea through implanted electrodes. Training was conducted in an effort to establish DC conditional relations and then to test for auditory–visual equivalences (DA and DB). The results of this preliminary study were promising but mixed. The 2 prelingually deaf children never mastered the prerequisite DC baseline via a simple differential reinforcement procedure. The 2 postlingually deaf adolescents did master the DC baseline, but only 1 of them showed emergent DA and DB auditory–visual relations. Thus, the preliminary study posed a number of questions concerning individuals with deafness and cochlear implantation.

The present four-experiment series sought to follow up on the preliminary work of da Silva et al. (2006). Questions asked included: (1) To what extent could postlingually deaf children exhibit auditory–visual stimulus equivalence classes given the type of training and testing procedures that are common in studies of children without neurosensory disorders (e.g., pseudowords and nonrepresentational forms)? (2) Could prelingually deaf children (a) acquire auditory–visual conditional discriminations via a stimulus control shaping procedure (see McIlvane & Dube, 1992 for a discussion of this generic terminology) and (b) then exhibit emergent auditory–visual equivalence relations? (3) If auditory–visual conditional discriminations could be established in prelingually deaf children, to what extent would they exhibit other forms of generalized auditory–visual stimulus control, specifically ''exclusion'' (Dixon, 1977) and ''learning by exclusion'' (McIlvane & Stoddard, 1981)? (4) Could prelingually deaf children learn auditory–visual conditional discriminations involving electrically-delivered stimuli like those in the study by da Silva et al. (2006) if a stimulus-control shaping procedure was used to encourage auditory–visual learning?

GENERAL METHOD

Participants

Sixteen children with severe-to-profound neurosensory deafness with diverse etiologies participated. Deafness in most of the children occurred prelingually, but some children had acquired deafness postlingually (Experiment 1). All children had cochlear implants that were typically connected to a speech processor that presented electrical stimulation to a range of locations in the cochlea. None of the prelingually deaf children had acquired any formal sign language prior to implantation. The postlingually deaf children had lip-reading skills that assisted in their communication efforts. None of the children were considered to have significant intellectual disabilities beyond those ordinarily resulting from deafness (e.g., delayed development of language); all of them could speak to some degree, but there was substantial interparticipant variability in vocabulary and intelligibility of speech.

Surgical cochlear implantation was performed in a hospital in the state of São Paulo. In postoperative care, the children were seen periodically to monitor and/or to adjust the functioning of the implant. For the prelingually deaf children, the time between implantation and the studies reported here constituted the children's main experience with auditory stimuli.

Apparatus, Experimental Procedures, Stimuli, and Setting

Matching to sample was the primary procedure used in the experiments. Matching trials

were presented via a desktop computer (Macintosh Performa 6360) using a software package developed by Dube (1991, MTS®). The matching procedures used were auditory–visual, visual–visual, and/or combined auditory/visual–visual. Specifics of these procedures will be presented with the individual experiments.

In Experiments 1–3, naming tests were given after tests for class formation. Naming responses were recorded by a videocamera (Sony 220x digital zoom handycam) that framed the child's face. Naming responses were subsequently transcribed by the experimenter, and these data were compared against those collected by a second observer to assess reliability. The second observer was not familiar with the procedures and was not told the purpose of the experiment. Reliability was assessed on 37.5% of the naming trials (54/144). The mean agreement across participants was 85.2% (range 77.7% to 100.0%), calculated as the number of agreements divided by the total number of naming trials, multiplied by 100 (Kazdin, 1982).

The children's names and stimulus assignments are shown for each experiment in Figure 1.

Pretraining

Children in Experiments 1–3 (but not Experiment 4) were given pretraining to familiarize them with visual–visual and auditory–visual matching-to-sample procedures of the general type to be used in the experiment. On visual–visual pretraining trials, four familiar cartoon figures (Bugs Bunny, Homer Simpson, Goofy, He-Man) were presented in a delayed-sample identity-matching format (see McIlvane, Kledaras, Stoddard, & Dube, 1990 for the rationale for this matching-to-sample procedure variant). Each of these trials began with the presentation of four comparison stimuli—one each in each of four demarcated locations (approximately 5 cm × 5 cm square) in the corners of the computer monitor screen. After a 2-s delay, a figure identical to one of the comparison stimuli was displayed in a 5 × 5 cm square sample area in the center of the screen. Any responses occurring prior to the sample presentation had no programmed consequence.

Initially, an experimenter prompted choice via mouse click of the comparison stimulus identical to the sample stimulus, using a combination of verbal/gestural prompts and modeling. Eight such trials were presented, two with each of the four sample stimuli. Prompts were repeated if matching errors occurred or if responses continued to be exhibited prior to the presentation of the sample stimulus.

Subsequently, each child was exposed to a series of 16 delayed-sample trials in which the sample stimulus was an auditory–visual complex (a variant of a stimulus control shaping procedure pioneered by Sidman, 1977): one of the four familiar cartoon characters and its Portuguese name presented over the computer's external speakers in a feminine voice (''Pernalonga,'' ''Homer,'' ''Pateta,'' ''He-Man''). All other aspects of these trials were identical to the visual–visual trials. Auditory–visual sample stimulus pairs varied unsystematically across trials. On every trial, the auditory component was a stimulus that was to be related with the visual component, thus pairing the two temporarily. After the first four trials, the visual sample component was systematically reduced in intensity (i.e., faded out). When visual samples were no longer detectable, consistent correct matching was possible only if the procedure had sufficed to verify or establish (a) attending to and discrimination of the defining auditory components of the sample stimuli and (b) he relationship of the sample stimuli to their corresponding visual comparison stimuli.

Immediately following stimulus control shaping was a 4-trial auditory–visual matching-to-sample posttest (one trial with each of the four auditory–visual matching relations). If any errors occurred on the posttest, then the entire 20-trial sequence was repeated.

Programmed Consequences

Correct matching-to-sample selections were followed by immediate removal of the stimuli to be discriminated and a simultaneous presentation of a 2-s animated display of colored stars and a brief, computer-generated musical phrase. This display was then followed by a 1-s intertrial interval. During the intertrial interval, the entire computer screen was gray. Consequences following incorrect matching selections included removal of all stimuli, a 2-s screen blackout, and the intertrial interval.

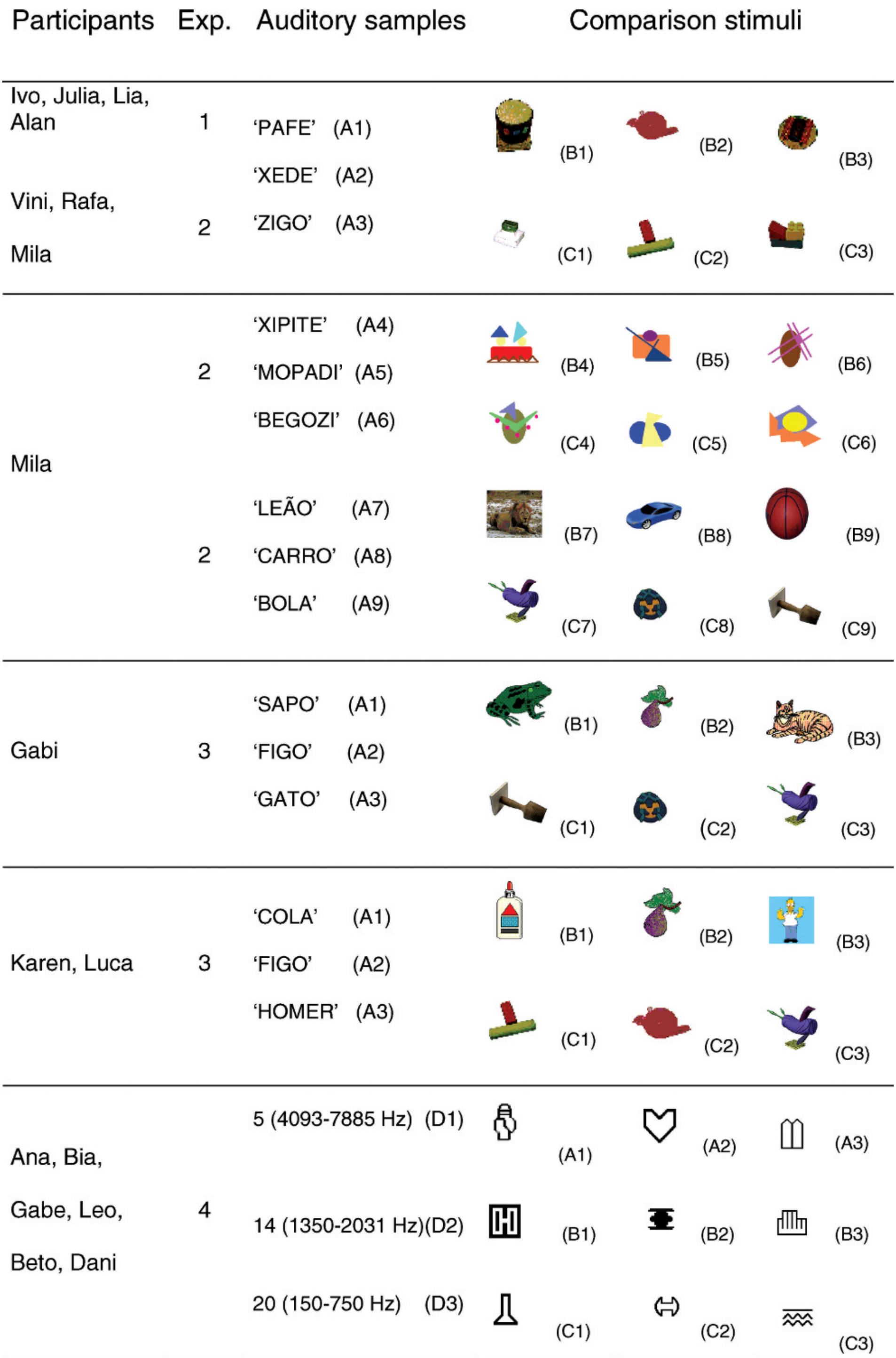

Fig. 1. Sample and comparison stimuli used in the experiments. In Experiments 1–3, the auditory samples were words and pseudowords. In Experiment 4, the sample stimuli were tones delivered by electrical stimulation of the cochlea; the tones were delivered to specific electrode sites indicated by the numbers and the frequency ranges are shown in parentheses.

Table 1

Characteristics of participants in Experiments 1, 2 and 3.

Participants	Gender	Age	Time since implant	Auditory deprivation	Implant model	Vocabulary scores [a]
		Experiment 1 (postlingually deaf)				
Lia	F	11–7	2–9	7–0	Méd-El® Short	90
Júlia	F	12–10	1–0	0–8	Méd-El® C40+	95
Alan	F	8–0	2–7	0–9	Med-El® C40+	95
Ivo	M	11–5	0–11	1–5	Méd-El® C40+	50
		Experiment 2 (prelingually deaf)				
Vini	M	4–10	1–5	3–5	Méd-El® C40+	90
Rafa	M	5–11	4–4	1–7[b]	Nucleus® 24	90
Mila	F	11–0	6–0	5–0[b]	Nucleus® 22	85
		Experiment 3 (prelingually deaf)				
Luca	M	11–10	8–1	3–9	Nucleus 24®	78
Gabi	M	10–0	5–4	4–8	Méd-El® C40+	63
Karen	F	10–9	6–11	3–10	Nucleus 24®	97

Note. Ages, auditory deprivation and time since implant are expressed in years-months.
[a] The values represent percentages of correct selections of 20 pictures conditionally upon spoken words.
[b] Congenitally deaf.

These forms of feedback constituted the only programmed consequences used during pretraining and training in Experiments 1–3. These consequences were supplemented by tangible reinforcers in Experiment 4.

Setting

All procedures were conducted in a quiet room at the hospital that the children visited periodically for evaluation and maintenance of the cochlear implant. Hospital staff scheduled the child's visit, and it was necessary to accommodate that schedule, fitting sessions in during free times. As such, there were occasional instances in which deviations from planned protocols were unavoidable. In certain cases, testing could not be completed as planned. In others, more than the planned numbers of baseline sessions were given when children became temporarily unavailable for sessions, which were otherwise conducted daily.

EXPERIMENT 1

Experiment 1 was a systematic replication of the procedures reported by da Silva et al. (2006). Whereas the stimuli in the earlier study were tones delivered electrically to the children's implants (i.e., nonspeech sounds) and Greek letters, those in this experiment were pseudowords and abstract colored forms. These stimuli are shown in the uppermost portion of Figure 1. The aim was to validate the procedure using sample and comparison stimuli comparable to those of many previous stimulus equivalence studies that have appeared in the literature (e.g., de Rose, de Souza, & Hanna, 1996; Sidman & Tailby, 1982; Spradlin & Saunders, 1986).

Method

Participants

Four children with profound postlingual neurosensory deafness participated. The upper portion of Table 1 presents their identifiers and characteristics. Auditory deprivation refers to the interval of time each participant lived without auditory stimulation. Prior to their participation in the experiment, all children received vocabulary pretests evaluating their ability to match 20 common pictures to their dictated names; all but Ivo scored at least 90% correct.

Matching-to-Sample Procedures

Following the pretraining described above, participants completed auditory–visual delayed-sample matching trials in which the pseudoword samples shown in Figure 1 were presented in a feminine voice over the computer speakers. Each trial began with the presentation of three comparison stimuli (also shown in Figure 1), displayed in three of four randomly selected corners. After a 2-s delay the auditory sample was presented and the computer repeated the pseudoword every 4 s until the child selected a comparison stimulus; trials had no time limit (i.e., no limited hold).

In addition, we used two forms of visual–visual matching procedures—identity matching and arbitrary matching. Identity matching (BB and CC—see Figure 1) was superimposed on the auditory–visual matching AB and AC (see below), during the stimulus control shaping procedure. The sample stimulus was an auditory–visual complex: one of the visual stimuli (for example, B2) and an auditory stimulus (for example, A2) presented over the computer's external speakers in a feminine voice; the comparison stimuli were the visual stimuli from Set B (in the AB training) or Set C (in the AC training). Arbitrary visual matching was used to test for equivalence class formation (BC and CB probe trials). On all visual–visual matching-to-sample trials, sample stimuli were presented in the center location. Comparison stimuli were presented in any three of the four corners, again randomly selected. This procedure also used the 2–s delayed-sample format.

Stimulus Equivalence: Baseline Training and Equivalence Tests

AB and AC baseline auditory–visual matching. AB and AC relations were initially taught separately via the stimulus control shaping method used in pretraining. The first 18-trial block taught only the A1B1 relation and the sample stimuli alternated between A1 (''PAFE''; 10 trials) and two stimuli used in the pretraining (''Pateta'' and ''Pernalonga''; 4 trials each). On each of these trials comparisons were B1 and the cartoon images of Pateta (Goofy) and Pernalonga (Bugs Bunny). The visual component of the sample was faded out across trials using the criteria described above. The second block added A2B2 training trials (10 trials) to the A1B1 (4 trials) and pretraining trials (2 trials each) and used the visual sample-stimulus fading procedure. The third training block mixed the A1B1 and A2B2 relations without presenting the visual components of the sample stimuli, which had been faded out in the previous trial blocks; differential feedback was presented following every choice. This constituted the first training of arbitrary matching (i.e., auditory sample to visual comparison). If more than one error occurred during arbitrary matching the third training block was repeated with visual sample-stimulus fading before arbitrary matching was attempted again. Once this accuracy criterion was reached in arbitrary matching, the A3B3 relation was taught using the same procedure.

This entire visual sample-stimulus fading procedure was then used to train the AC relations. Subsequently, AB (A1B1, A2B2, A3B3) and AC (A1C1, A2C2, A3C3) trials were mixed (three trials each) in a final training block in which no visual components of the sample stimuli were presented. As before, a 94% accuracy criterion was used throughout training. Occassionally, logistical considerations led us to slightly reduce this criterion (see below). After criterion was met in the final mixed AB and AC block, feedback was presented on a random-ratio 2 (RR 2) schedule (i.e., on a randomly selected half of the trials).

Class formation tests. After the accuracy criterion was met at this reduced level of feedback, class formation tests were conducted with relations BC (B1C1, B2C2, B3C3) and CB (C1B1, C2B2, C3B3); these constitute combined tests for symmetry and transitivity (Sidman & Tailby, 1982). In test-trial blocks, (a) six trials assessed the previously established AB and BC baseline relations with feedback provided on all the trials and (b) nine trials tested potentially emergent relations (BC or CB) with no programmed consequence following selections (i.e., only 40% of the trials in the block could include reinforcement). If scores were less than 100%, then the BC and CB tests were repeated once.

Naming tests. After these class formation tests, naming tests displayed either the B- or C-stimulus twice in the center of the screen with the auditory stimulus ''O que é?'' (''What is this?'') presented over the computer's speakers with the same feminine voice. No programmed consequences followed responses on naming probe trials.

Results and Discussion

Matching to Sample

Figure 2 shows that all of participants learned the AB and AC baseline relations, in most cases with few errors during training. The teaching procedure thus proved effective despite the fact that attending to the auditory sample was not required until the final steps of the stimulus control shaping program. This generally accurate performance was likely the result of (a) pretraining on the same tasks with familiar stimuli and (b) the children's learning in other contexts to attend to stimuli whose onsets and offsets were positively correlated with effective discriminative stimuli.

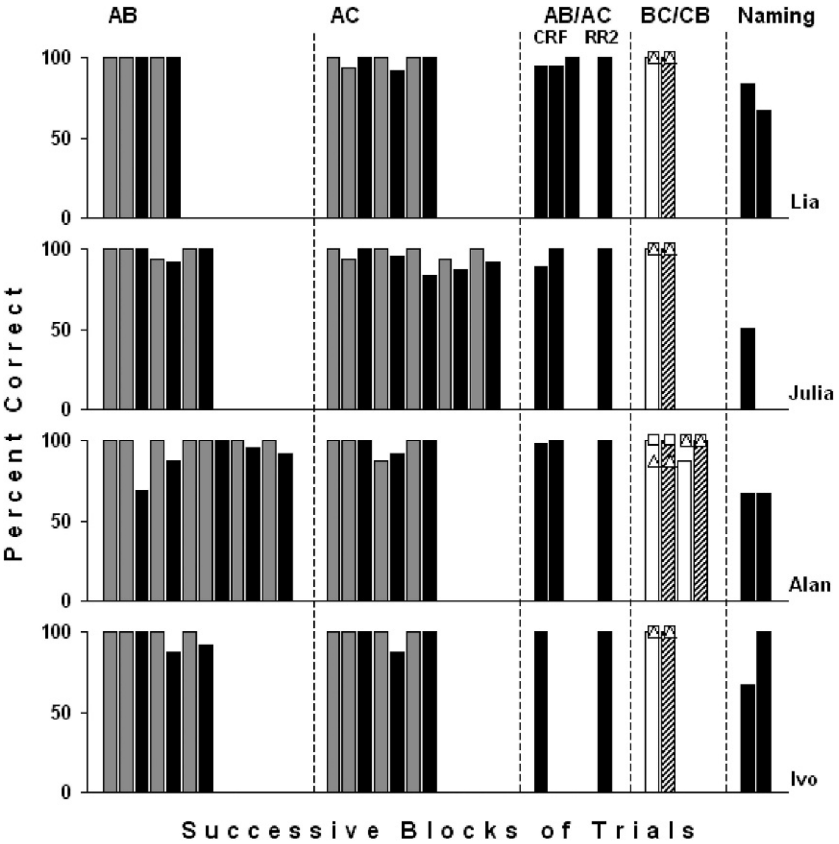

Fig. 2. Percent correct responses across successive blocks of teaching and testing in Experiment 1. Gray bars indicate blocks in which the visual component of the sample stimulus was gradually faded out over trials and the black bars show blocks in which sample stimuli were exclusively auditory. On the equivalence probes, triangles and squares on the BC trials (white bars) and CB trials (hatched bars) indicate accuracy levels on baseline trials during testing. The first bar on the naming probes indicates point-to-point correspondence with the recorded sample (that is, in the presence of each B or C stimulus the participant spoke the same word that had been dictated as the corresponding sample during training). The second bar indicates the percentage of occasions on which the participants used the same word to name the two stimuli in the same class.

On equivalence tests, all children demonstrated emergent BC and CB matching consistent with the matching relations defined in baseline training.

Naming

The left bar under the ''Naming'' heading of Figure 2 indicates the percentage of naming probe trials on which the participant spoke the word previously dictated as the A-sample stimulus to which the B- and C-stimuli had been related through training (e.g., ''PAFE'' when presented with B1 or C1 as the sample stimulus). Children always emitted a verbal response on these trials, but much of the naming had no point-to-point correspondence with the particular A-sample and thus was not scored as correct. The right bar under the ''Naming'' heading indicates the percent of naming probe trials in which the participant gave the same name to the two stimuli related by equivalence on the matching tests (e.g., ''ZIGO'' emitted in the presence of both B3 and C3). This was a measure merely of consistency of within-class naming. It does not necessarily indicate that the name consistently applied was the one presented on auditory–visual matching-to-sample trials (i.e., ''NIDA'' emitted in the presence of both B3 and C3 would also count as ''consistent'' naming, although not corresponding to A3; however, saying ''ZIGO'' in the presence of B3 and ''NIDA'' in the presence of C3, would count as an inconsistency). While common naming

often occurred with 3 of the participants, it virtually never did so with Julia, despite perfect performance on the equivalences tests.

EXPERIMENT 2

This experiment was a systematic replication of the previous experiment using prelingually deaf rather than postlingually deaf participants.

Method

Participants

The participants were 3 children with profound bilateral neurosensory deafness. Other characteristics appear in the middle portion of Table 1. Note that all of the children had developed some listening skills following cochlear implantation. They all achieved reasonably high scores on the initial tests of their ability to identify 20 pictures of common objects when the name of each object was presented in the auditory format.

Procedure

The methods were identical to those of Experiment 1, with two exceptions: First, the learning criterion was lessened to 78% correct for Vini, the youngest child. The criterion was lessened for two reasons. First, time constraints presented a practical problem of accomplishing the training and testing within an unusually short time period. Second, and more importantly, it appeared that inaccurate performances often followed long periods of highly accurate performance, suggesting control by competing contingencies (cf. McIlvane & Dube, 2003 for a discussion of this phenomenon). When the task requirements were relatively novel, however, accurate performances were typically observed. With this rationale, testing went forward despite imperfect baseline performances. The second difference from Experiment 1 was that Rafa was not exposed to RR 2 and the equivalence test protocol was modified. Blocks presented only BC and CB tests under extinction conditions. The child was instructed that feedback would not follow trials within these blocks, and he received a toy after the tests.

Results

Training and test results are displayed in Figure 3 with the exception of Rafa's CB test data, which were lost due to a technical problem. These data show that Vini exhibited emergent BC and CB relations on the probe trials and Rafa did so on the BC trials. Direct experimenter observation of Rafa on CB trials also indicated highly accurate CB responding. Mila, however, obtained low or intermediate scores on BC and CB probe trials, despite repeated testing and highly accurate performance on baseline trials (Figure 3, third row). Neither Vini nor Mila exhibited high accuracy in naming performances. Both Vini and Rafa showed 100% consistency in naming both B and C stimuli (i.e., giving the same name to each stimulus on each trial; rightmost bars).

In follow-up work with Mila, we conducted two systematic replications of the procedures, the results of which are shown in the lower two rows of Figure 3. The first replication was conducted with three-syllable instead of two-syllable auditory sample stimuli (see Figure 1). The rationale for this was that such stimuli, having more distinctive features, might be more easily discriminable. Neither BC nor CB relations emerged (Figure 3, Row 4, Mila-2).

In the second replication, we introduced picture (Set B) stimuli (*lion*, *ball*, and *car*) that Mila had already learned to relate to corresponding spoken words (Set A) in Portuguese prior to the experiment (one technique for promoting rapid procedural learning of conditional discriminations; cf. McIlvane, Munson, & Stoddard, 1988). Set C was composed of abstract form comparison stimuli. Here, the goal was merely to expand potentially extant extraexperimental classes—relating nonrepresentative forms to recorded names that corresponded to the pictures and vice versa. When the procedures were repeated with these modifications, emergent BC and CB performances were observed (Figure 3, Row 5, Mila-3), and naming performances improved.

Discussion

All children in this experiment acquired auditory–visual matching performances. These results differed substantially from those reported by da Silva et al. (2006), in which children with prelingual deafness did not acquire such performances. These different outcomes may be due to the different teaching procedures employed. In the earlier study, no pretraining was conducted and da Silva et al. used a simple differential reinforcement procedure rather

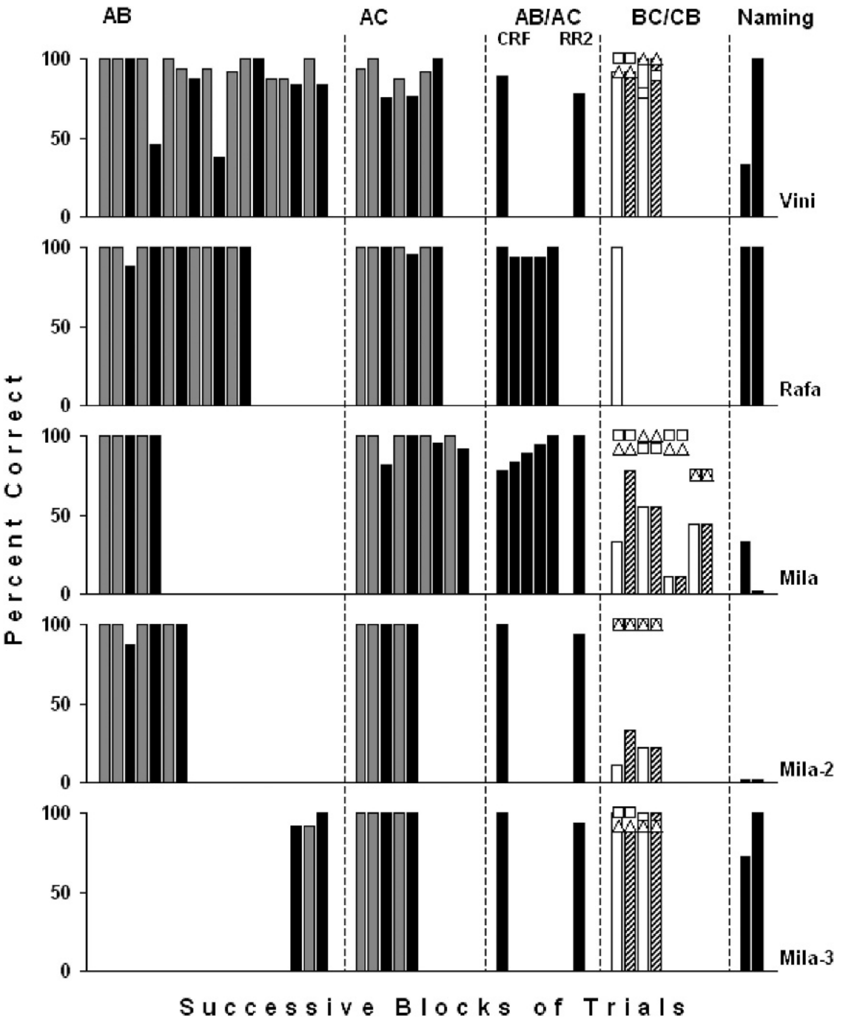

Fig. 3. Percent correct responses across successive blocks of matching-to-sample teaching and testing trials in Experiment 2 (see Figure 2 caption for further details). Naming probes show point-to-point correspondence with the dictated sample (left bar) and use of the same word to name each class member (right bar). Rows 4 and 5 show data from followup work with Mila (see text).

than the stimulus-control shaping procedure used here. The present findings do not establish if one or both of these changes were responsible for the superior discriminations.

Regarding Mila's initial failure to exhibit equivalence classes on the original procedure and her subsequent success on the second systematic replication, one may not conclude that her success with the replication was due to the introduction of stimulus–stimulus relations with extraexperimental histories. These findings were obtained after two prior exposures to auditory–visual matching procedures. Thus, there was no control for the passage of time, for the effects of extended auditory–visual discrimination training, or for the number of new arbitrary matching performances to be learned. Any or all of these variables might conceivably have been responsible for Mila's success on her third equivalence test.

EXPERIMENT 3

Experiment 2 showed that children with prelingual deafness could acquire auditory–visual conditional relations with few errors by direct teaching using a straightforward stimulus control shaping procedure. This auditory–

visual baseline established the prerequisites for exploring further the auditory–visual capabilities of such children. Our interest in Experiment 3 was whether prelingually deaf children would exhibit the phenomenon of ''exclusion.'' Exclusion refers to matching relations that spontaneously emerge when the matching trial includes (a) an experimentally undefined comparison stimulus (i.e., not defined in relation to any sample by the programmed contingencies), (b) a comparison stimulus that has been so defined, and (c) an undefined sample stimulus (i.e., in relation to any comparison stimulus). A variety of hearing human populations with varying levels of language development have been studied in exclusion research (Dixon, 1977; da Costa, Wilkinson, de Souza, & McIlvane, 2001), and virtually all individuals of these populations select undefined comparison stimuli immediately and consistently in relation to undefined sample stimuli. Moreover, it is often observed that a history of exclusion may establish new matching relations between the formerly undefined sample and comparison stimuli that are exhibited even in the absence of a defined stimulus to be excluded. This phenomenon is called ''learning by exclusion'' (McIlvane & Stoddard, 1981; Ferarri, de Rose, & McIlvane, 1993). Experiment 3 asked whether children with prelingual deafness and lengthy histories of early auditory deprivation would exhibit similar capabilities.

Method

Participants

Three children with profound prelingual neurosensory deafness participated (see Table 1). Each received a vocabulary test similar to that described in the prior experiments. Participant Karen achieved high accuracy scores and Gabi and Luca scored at an intermediate level.

Procedure

The matching-to-sample procedures and general design of this experiment were essentially the same as those of Experiment 2, except that the more typical sample-first procedure (cf. Sidman & Tailby, 1982) was used instead of the delayed-sample procedure. The auditory–visual relations AB and AC were established, and then a test was conducted to evaluate the emergence of visual–visual relations BC and CB. Figure 1 shows specific sample and comparison stimuli used with each child.

The exclusion procedure resembled that used in a study of exclusion with preschool children (McIlvane, Munson, & Stoddard, 1988). The AB training entailed auditory–visual relations with potential extraexperimental histories. Figure 1 shows that Gabi, for example, learned initially to match *frog*, *fig*, and *cat* to corresponding dictated Portuguese words *(''sapo,'' ''figo,''* and *''gato'')*.

The only other difference of note between this experiment and Experiment 2 was the nature of the teaching procedure used to establish the baseline relations. Briefly, the children first were exposed to a block of 8 trials presenting the same sample (A1) and comparison stimuli (B1, B2) on each trial. Selecting B1 was prompted on the first trial by presenting it alone; feedback was provided on all 8 trials. In the next 8-trial block, the dictated sample stimulus was changed (A2) but the comparison stimuli were not, and selection of B2 was specified as correct. The child could select B2 either because the A2B2 relation had been established extraexperimentally or because s/he could exclude comparison B1. After a block of such trials, the A1B1 and A2B2 relations were intermixed for a 16-trial block while a third comparison stimulus, B3, was displayed with B1 and B2. Thereafter, the A3B3 relation was introduced in the same manner, permitting exclusion, and intermixed as before.

The procedure used to teach the AC relations was virtually identical to that used to teach the AB relations, except that these relations were entirely arbitrary (i.e., involving abstract forms with no extraexperimental history). Errorless performance in learning the A2C2 and A3C3 relations, however, could occur only if the child excluded previously defined comparison stimuli on the first trial of a block in which the sample stimulus changed. At the end of AC training, both AB and AC trials were intermixed in 18-trial blocks. Such blocks were repeated until the child achieved a 94% accuracy score. Then, the schedule of programmed consequences was changed from continuous reinforcement to RR 2. The criterion for proceeding was also 94% under these conditions. Finally, equivalence tests (BC and CB) and naming tests were conducted as in the previous experiment.

Results and Discussion

Gray bars of Figure 4 show the training blocks in which AB or AC relations could have been learned by exclusion. Participants made no errors in any of these blocks, thereby showing good evidence of exclusion and learning by exclusion. Accurate performance was maintained with little or no disruption when AB and AC trial types were intermixed and intermittent consequences were scheduled. Scores on BC (white bars) and CB trials (hatched bars) were high, thus confirming the existence of three ABC equivalence classes. For 2 children, results on naming tests were similar to those of Experiment 2 (i.e., low-to-intermediate accuracy). Luca, however, exhibited perfect scores on naming tests—the only child to do so of all that were tested in Experiments 1–3. All 3 showed 100% consistency in naming B and C stimuli.

Regarding the highly accurate performance during training, it is possible that the initial accuracy on AB relations was due in part to extraexperimental experience. The perfect accuracy on all trials in initial AC training had to be due to exclusion, however, because the sample and comparison stimuli had no previously defined relation to each other. The 100% scores achieved by all 3 children thus demonstrated errorless learning by exclusion.

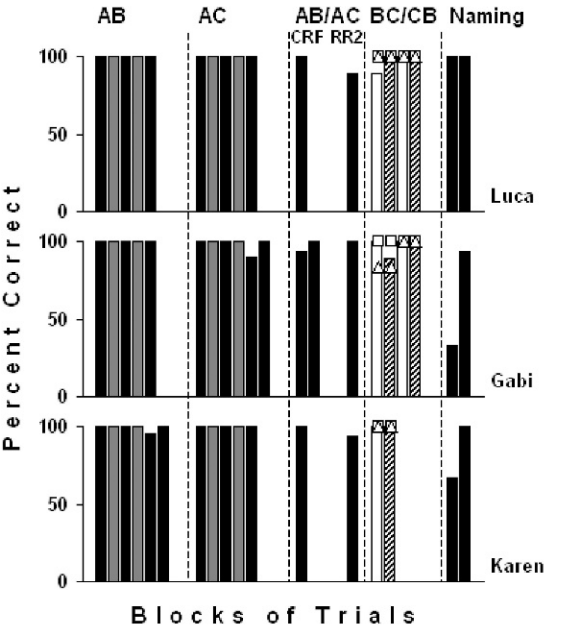

Fig. 4. Percent correct responses across successive blocks of matching-to-sample teaching and test trials in Experiment 3. Gray bars show the results of blocks on which exclusion performance was possible. On the equivalence probes, triangles and squares on the BC trials (white bars) and CB trials (hatched bars) indicate accuracy levels on baseline trials during testing. Naming probes show point-to-point correspondence with the dictated sample (left bar) and use of the same word to name each class member (right bar).

EXPERIMENT 4

Given our demonstrations of auditory–visual equivalence relations in prelingually deaf children using procedures typical of equivalence research with hearing children, the question arose concerning failure of da Silva et al. (2006) to demonstrate acquisition of auditory–visual conditional discriminations involving tonal stimuli. If children were given help in learning to attend to such stimuli (i.e., via a stimulus control shaping procedure), would they be more likely to acquire auditory–visual baselines that would permit tests of stimulus equivalence? Experiment 4 was initiated to replicate systematically the class-expansion study reported by da Silva et al., adding stimulus control shaping to teach the baseline auditory–visual relations. Given the nature of the experimental task and population, a very careful, highly systematic approach to stimulus control shaping was employed.

Method

Participants

Six children with prelingual deafness participated. Table 2 presents their characteristics. One difference was use of a translated version of the Peabody Picture Vocabulary Test–Revised (PPVT–R; Dunn & Dunn, 1981), administered in order to assess the children's ''listening'' ages (i.e., age-comparable functioning). Although performance on the PPVT–R indicated that all children had learned a number of name–referent relations prior to the experiment, their scores were substantially lower than those expected for their chronological ages, due likely to effects of deafness early in the typical language development period and only resolved (to some degree) by cochlear implantation.

Procedure

Overview. The procedure was implemented in two phases. The first phase was conducted

Table 2

Characteristics of prelingually deaf participants in Experiment 4.

Participants	Gender	Age (years-months)	Time since implant	Auditory deprivation	PPVT–R[a] scores
Leo	M	8–2	3–6	4–8	2–9
Bia	F	6–4	3–3	3–1	3–0
Gabe	F	7–5	3–7	3–10	3–1
Beto	M	9–1	2–3	6–10	3–3
Dani	F	9–3	3–7	5–8	3–4
Ana	F	5–8	2–8	3–0	2–2

Note. All participants in this experiment received Nucleus 24® cochlear implants. Ages and periods of time (auditory deprivation and postimplant period) are expressed in years-months.

[a] Peabody Picture Vocabulary Test–Revised (Dunn & Dunn, 1981).

to establish stimulus classes with three sets of visual stimuli (A, B, C: nonrepresentative black-and-white forms, shown in Figure 1) presented on a computer monitor with control software that was described in the previous experiments. Visual–visual AB and AC relations were taught directly, and BC and CB relations were tested for emergence without further training.

In the second phase, auditory–visual DC relations were taught and tests for emergent DA and DB relations constituted the class expansion tests. D stimuli were electrical pulses delivered directly into the cochlea. To present these stimuli, the speech processor was turned off and a second computer, interfaced with the cochlear implant, generated the auditory stimuli. Electrical pulses were delivered once per second to three different single-electrode cochlear positions (i.e., D1, D2, and D3): basal, medial and apical. These stimulus positions were selected to produce easily discriminable tonal stimuli. To further encourage acquisition of auditory–visual relations, tangible reinforcers (tokens with backup reinforcers) were added to the consequences used in previous experiments. The tokens were delivered by hand by the experimenter coincident with the computer-generated consequences described in the preceding experiments according to schedules detailed below. The tokens could be accumulated and traded after each session for a small toy or activity.

Phase 1: Visual–visual matching-to-sample baseline training and equivalence tests. Visual–visual matching trials were presented in the sample-first arrangement. The children were exposed first to a block of 8 trials displaying the same sample (A1) and comparison stimuli (B1, B2) on each trial. Selecting B1 was prompted on the first trial by presenting it alone. All selections of B1 were followed by the auditory–visual display and delivery of a token. In the next 8-trial block, the visual sample stimulus was changed (A2) but the comparison stimuli were not, and selection of B2 was specified as correct (cf. Saunders & Spradlin, 1990). When the comparison stimuli were selected reliably, A1B1 and A2B2 trial types were intermixed. When each comparison stimulus was selected reliably (i.e., 100% accuracy) in relation to its corresponding sample stimulus, then the A3B3 trial type was introduced, the number of trials was increased to 18, and training proceeded in the same manner. At the end of this training, three comparison stimuli were presented on each trial (B1, B2, B3) and three samples (A1, A2, A3) were presented in an unsystematic order across trials. The mastery criterion was 100%. AC training was conducted in the same manner. Thereafter, AB and AC trial types were intermixed, and the continuous reinforcement schedule was thinned to RR 3. This was done in preparation for testing potentially emergent BC and CB relations on unreinforced probe trials.

Probe sessions contained 6 probe trials of a single type (e.g., BC or CB), conducted in extinction and interspersed within 15 baseline trials. Probe responding that was consistent with the AB and AC baseline relations would indicate the formation of three-member ABC all-visual equivalence classes.

Phase 2: Teaching auditory–visual relations and testing for class expansion. Prior to this phase, participants were informed that their speech processor would be disconnected and that the matching-to-sample task would now involve listening to tones. Procedures of this general type were typical of those used in the

evaluation and monitoring of the child's cochlear implant. In this context, providing notice of the change was deemed unavoidable.

The auditory–visual stimulus control shaping procedure adapted an already well-developed routine that was used to tune the implant. On every auditory-matching teaching trial, an auditory stimulus was presented, and the child was required to indicate its presentation by raising his or her hand. Simultaneous with the tone pulses, a visual sample stimulus was presented in the center of the screen. A response to the visual sample was followed by (a) presentation of visual comparison stimuli from Set C (one of which was identical to the visual component of the sample) and (b) an opportunity to make a matching-to-sample selection. Over trials, the visual component of the sample stimulus was faded out progressively. At the final program step, the visual sample was completely removed and auditory–visual arbitrary matching was required in order to meet the programmed contingencies.

The stimulus-control shaping procedure used in this experiment was somewhat different from those described in earlier experiments. Given the past failures reported by da Silva et al. (2006) with similar children and tasks, the MTS® package was used to arrange a more gradual shaping series and to incorporate a backup feature, that is, returning to earlier program steps if errors were made. The criterion at the final performance was 100% accuracy in a block of 18 trials. When this was achieved, the AB, AC and DC relations were intermixed within the same trial block. After criterion was met, the schedule of reinforcement was shifted to RR 3 in preparation for the DA and DB class expansion tests.

Results and Discussion

The left portion of Figure 5 shows the results of Phase 1, the visual–visual training and testing for 5 of the 6 participants. It shows a somewhat variable pattern of acquisition of the AB and AC relations across participants and different degrees of disruption when these relations were intermixed. However, all children ultimately acquired and maintained these visual–visual relations. On tests for BC and CB relations, all children showed emergent relations, either immediately or in repeated testing in extinction (gradual emergence).

The right portion of Figure 5 shows the results of Phase 2, beginning with training of the DC auditory–visual matching relations. The stimulus control shaping procedure (gray bars) proved effective in establishing these relations. Performance during shaping was not errorless, but the procedure was effective in forestalling error patterns and protracted failures to acquire auditory–visual relations (cf. Sidman & Stoddard, 1967; Stoddard & Sidman, 1967; Stoddard, de Rose, & Mcilvane, 1986). When shaping was discontinued (black bars), some children exhibited temporary declines in accuracy on DC trials, but performance recovered quickly. When the AB, AC, and DC relations were intermixed, some children showed initially imperfect performances, but all ultimately met criterion. Further baseline disruption was observed when the intermittent schedule was introduced; however, this baseline also was recovered quickly with all children. When DA and DB tests for class expansion were conducted, all 5 of these children showed emergent relations, again either immediately or gradually in repeated testing.

Figure 6 shows a different pattern of results with Ana, the 6th participant. Acquisition of AB relations was comparable to that shown by the other children (Figure 5) but acquisition of AC relations was not. Despite initially high accuracy scores, her AC performance was inconsistent across training blocks and acquisition was thus delayed substantially compared with that of the other children. Relatively delayed acquisition was noted also when the AB and AC relations were intermixed. Nevertheless, Ana ultimately acquired consistent visual–visual relational responding. Moreover, she exhibited gradually emergent BC and CB relations in a manner similar to that observed with several other children.

As with the other 5 participants, the stimulus control shaping procedure proved effective in establishing DC auditory–visual matching relations with Ana. When shaping was discontinued, however, she exhibited temporary declines in accuracy on DC trials, similar to those observed during acquisition of AC relations. Further disruptions in baseline relations accuracy were observed during intermixture of the AB, AC, and DC relations and during introduction of the intermittent reinforcement schedule. After protracted exposure, Ana met

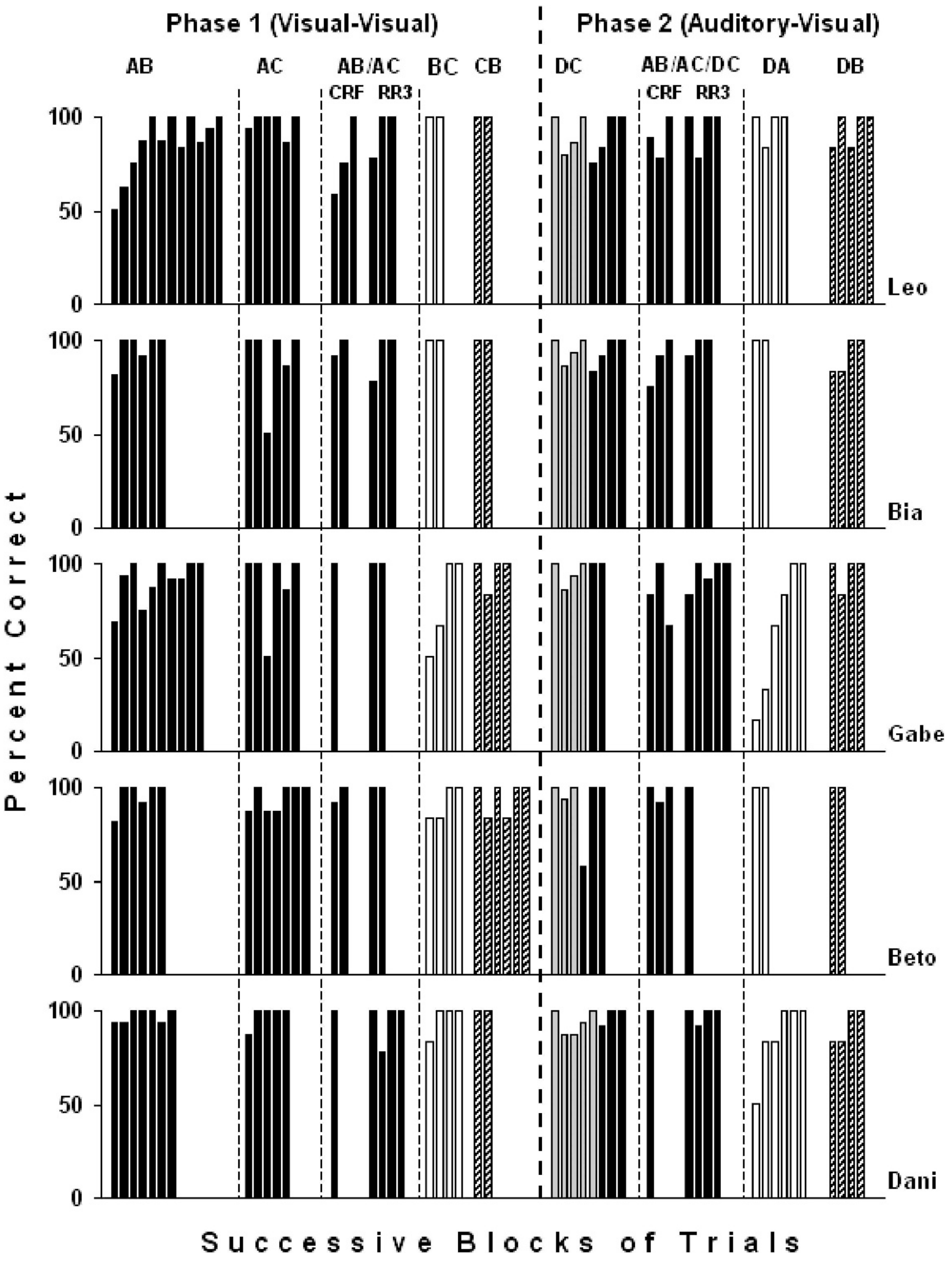

Fig. 5. Percent correct responses across successive blocks of matching-to-sample teaching and test trials in Experiment 4 for 5 of the 6 participants. The left portion shows the results of all visual training and testing (Phase 1). The right portion shows results of auditory–visual training and testing (Phase 2). White and hatched bars indicate types of probes on tests of class formation in Phase 1 (BC and CB) and class expansion in Phase 2 (DA and DB).

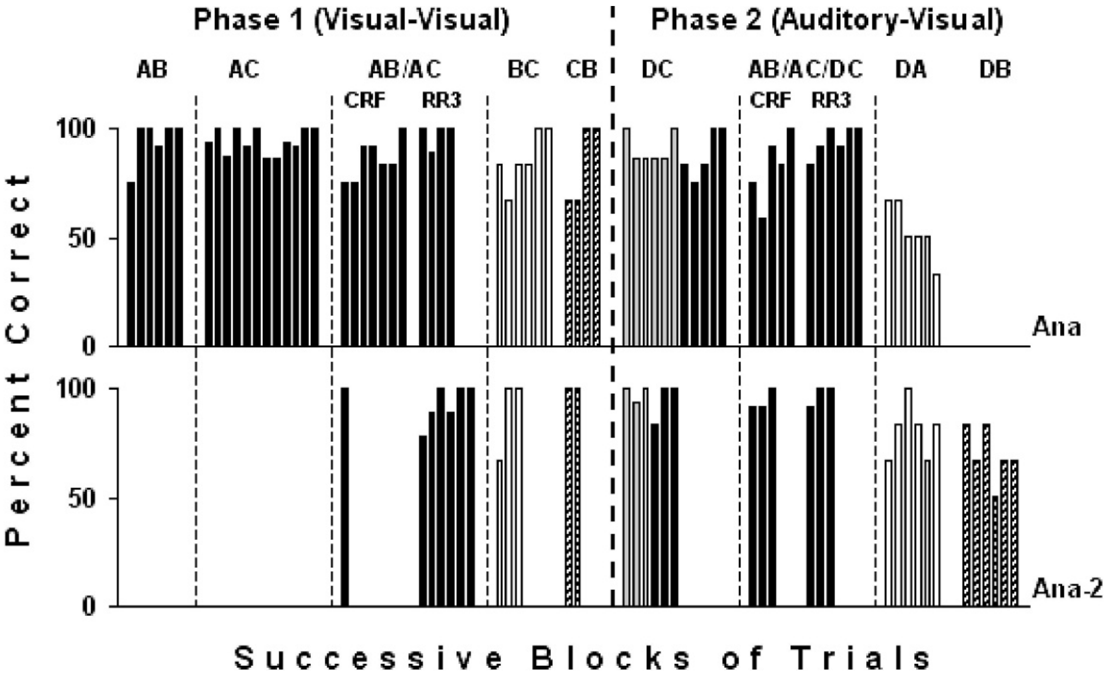

Fig. 6. Percent correct responses across successive blocks of matching-to-sample teaching and test trials in Experiment 4 for Ana (the 6th participant). The two rows show data from the first and second exposures to the procedures, respectively.

the criterion for advancement to the DA class expansion tests.

On the DA tests, the outcome was negative, thus differing from that of the other 5 children. Following immediately was retraining of all baseline relations, a second positive outcome on BC and CB probes (see Figure 6, second row), and a repetition of the DA class expansion test. Scores on the latter improved relative to the first round of DA probes—even achieving 100% during the third probe block, but stability was never achieved. Performance on subsequent DB probes was similarly imperfect.

There appears to be no compelling reason to attribute Ana's imperfect class expansion scores to effects of prelingual deafness. Occasional failures of equivalence class formation are sometimes reported with normally capable children. Note that Ana was the youngest child tested in this experiment, had the lowest PPVT–R score, and had by far the greatest difficulty in meeting the criterion in acquiring the baseline relations. Any or all of these variables might have been important in accounting for the differences between her results and those obtained with the other children.

Comparing the results of Experiment 4 to those of the prior three experiments, the major differences appear to be (a) greater difficulty in acquiring and maintaining both auditory–visual and visual–visual baseline relations and (b) stronger tendencies toward gradual emergence on equivalence probe trials. These differences may have been due to the abstract nature of both the auditory sample stimuli (tones) and the visual comparison stimuli (black-and-white nonrepresentative forms) (cf. Holth & Arntzen,1998, for an illustration of the role of stimulus familiarity in promoting class formation). The tasks in the prior experiments, by contrast, involved dictated words and color forms that may have been easier for the children to discriminate. Had we arranged to teach baseline relations involving more than one sample-comparison set (e.g., DB and DC), it is possible that we would have seen more robust class expansion (cf. Saunders, Wachter, & Spradlin, 1988).

GENERAL DISCUSSION

The present series of experiments has demonstrated convincingly that children with both postlingual and prelingual deafness and cochlear implants can (a) acquire auditory–visual and visual–visual conditional discriminations using discrimination training regimens that were similar in character to those used with hearing populations, and (b) subsequently exhibit both cross-modal and intramodal equivalence relations. This study also demonstrated that prelingually deaf children may exhibit exclusion performances, which has been related by Wilkinson, Dube, and McIlvane (1996) to the so-called ''fast mapping'' that typically occurs in the course of language acquisition in normally developing children (Carey & Bartlett, 1978; Golinkoff, Mervis, & Hirsh-Pasek, 1994; Markman, 1987). Thus, children with deafness and cochlear implants resemble their hearing peers in fundamental respects pertinent to the development of symbolic functioning. Indeed, there was clear evidence that conditional relations learned in the present study were in fact symbolic rather than some limited form of ''if–then'' relations (Sidman & Tailby, 1982).

These promising findings notwithstanding, the data on the development of emergent naming performances associated with auditory–visual equivalence classes in Experiments 1–3 were not typical of those often reported with similarly-aged hearing children. Whereas the auditory–visual matching baselines were often highly accurate, many children exhibited naming accuracy that was quite low. Thus, we observed a number of examples of independence in speaker and listener repertoires, recalling Skinner's (1957) theoretical analysis of verbal behavior and occasional reports in the experimental literature (e.g., Lee, 1981).

Do children with deafness and recent cochlear implants comprise a population that is particularly well suited to address basic questions of possible speaker–listener repertoire independence? In our view, children with prelingual deafness could be a potentially useful population if they were (a) studied early in life, prior to extensive experience that might provide other routes to learning symbolic relations, (b) available for study immediately or shortly after cochlear implantation and (c) not previously exposed to sign language or other formal communication systems. Children with deafness and cochlear implantation offer the advantage of having a well-defined sensory disorder that is separable from the global behavioral retardation that has been a common feature of populations in which a speaker–listener repertoire independence has been demonstrated (Guess, 1969). As compared to the latter population, quasi-longitudinal studies with prelingually deaf users of cochlear implants might be accomplished in a shorter, more practically achievable time frame.

The findings reported in this study may also interest researchers of basic stimulus control processes and applications of behavior analysis in instructional technology. Even after apparently successful cochlear implantation, some children continue to exhibit communication deficits (usually measured in terms of speech perception and speech recognition), relative to their normally developing peers (Kileny, Zwolan, & Ashbaugh, 2001; O'Donoghue, Nikolopoulos, & Archbold, 2000; Svirsky, Teoha, & Neuburger, 2004). As yet unpublished findings from our laboratory have demonstrated that children may obtain low scores in echoic and naming relations even 18 months postimplantation. The results of our Experiments 1-3 also showed naming difficulties despite laboratory control conditions, highly accurate conditional discrimination baselines, and documented equivalence classes with the very dictated words to which the children responded on auditory–visual matching trials. Such behavioral deficits continue to be poorly understood, especially given that children receiving cochlear implants seem to have substantial learning potential, as exemplified in the present study. It seems likely that methods of the experimental analysis of behavior could help to clarify these deficits and to provide a foundation for effective prescriptive programming.

To conclude, we note that the research reported here was conducted without major difficulty within the routines of a hospital setting. Given today's frequent emphasis on inclusion of children with disabilities in regular classrooms, access issues will be important to researchers interested in the behavior of children with deafness and cochlear implantation. The need for occasional maintenance of the implant creates a natural oppor-

tunity for scheduling behavioral research, provided the procedures can be implemented without disruption of the hospital routine as we achieved in the present case. In turn, the behavioral researcher might be in a position to accomplish translational and/or applied research that will be of interest and potential help to other disciplines concerned with establishing or reestablishing functional hearing in children with congenital or acquired deafness.

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Received: November 13, 2006
Final Acceptance: January 14, 2008