Published in final edited form as:

Infancy. 2018 ; 23(3): 410–431. doi:10.1111/inf.12227.

Temporal Responsiveness in Mother-Child Dialogue: A Longitudinal Analysis of Children with Normal Hearing and Hearing Loss

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Abstract

Dialogue between conversational partners, including mothers and their children, is precisely timed. The predictability of this timing is important for establishing and maintaining interaction, communication, and learning. This longitudinal study examines changes in the response latency of utterances in dialogue between mothers and their normal hearing and hearing impaired children between 4 and 60 months of age. Mothers and their children showed parallel developmental trends, responding to each other more quickly at older ages. Beyond these age-related group effects, significant dyadic effects were found in which individual children's latencies were related to those of their mothers, and vice versa. Developmental patterns did not significantly differ across hearing status groups, which may reflect the role of early identification and intervention in promoting positive developmental outcomes.

Keywords

Mother-child interaction; hearing loss; turn-taking; speech; longitudinal

Conversational interactions are fundamentally a temporal phenomenon in which partners' speech acts, gestures, facial expressions and other behaviors form contingent and reciprocal sequences. The temporal structure of these interactions is precise, with minimal gaps and overlaps between conversational turns (Sacks, Schegloff, & Jefferson, 1974). At a computational level, such coordination is a challenge. Skilled language users, must integrate auditory, visual, and conceptual processes, and coordinate them with rapid multimodal action in real-time (Levinson & Torreira, 2015). These challenges are amplified for the developing child who must learn such rapid coordination dynamics, while simultaneously learning to produce and comprehend language and other communicative acts.

The human ability for turn-taking is broadly observed, suggesting a somewhat universal ability. Despite structural differences across languages, turn-taking remains a common principle of all human communication. Evidence from comparative biology demonstrates that vocal or gestural turn taking is common across primate species, suggesting deep phylogenetic roots to this capacity for interaction (Levinson, 2016). Furthermore, at the level of ontogeny, contingent vocal interactions, in the form of proto-conversations, emerge early in infancy prior to the attainment of linguistic competence (Jasnow & Feldstein, 1986; Rochat, Querido, & Striano, 1999).

This kind of coordination clearly requires learning: children must attune to the temporal structure of dialogue at a variety of levels. At a macro level, cross-cultural studies have identified both culturally specific and culturally universal characteristics in the temporal structure (e.g., the degree of synchronous and contingent vocalization) of parent-child dialogue (Keller, Otto, Lamm, Yovsi, & Kärtner, 2008). At a micro level, attunement in the timing of conversational turns occurs as a function of individual bidirectional influences between partners in individual dyads (Welkowitz, Bond, Feldman, & Tota, 1990).

Exposure to this contingent behavior and the acquisition of this coordination are important for the developing child. In parent-child interaction, the adult caregiver is typically skilled at this kind of coordination, offering a potential source of input for learning such interactions. The achievement of successful coordination has broad developmental implications (Tarabulsky, Tessier, & Kappas, 1996), and mounting research suggest that this kind of parental input is crucial for obtaining it. Contingent vocal responding on the part of the caregiver has been correlated with mother-infant attachment (Jaffe et al., 2001), as well as more basic functions in speech and language development (Bloom, Russell, & Wassenberg, 1987; Goldstein & Schwade, 2008; Goldstein, King, & West, 2003; Gros-Louis, West, Goldstein, & King, 2006).

However, this work does not make it clear how such sensitivity and coordination develop. In this regard, infants must solve two problems. First, they must learn that others' behavior is predictable from their own, and that they should also respond contingently to communicative acts. That is, they must learn *that* the other is going to respond at all, and they must do the same (the *predictability* of communicative behavior). This has been the emphasis of much of the aforementioned prior work on the importance of contingent responding for broader outcomes (Bloom et al., 1987; Goldstein & Schwade, 2008; Gros-Louis et al., 2006). Second, and more pertinently for the present study, children must learn to coordinate their action *in time* (and they must detect if others are similarly coordinated). That is, it is not enough to respond whenever the partner has spoken or acted, they must be closely time-locked (the *coordination* of behavior).

Each of these problems has important developmental implications. The focus of present study is on the latter problem of coordination, and in particular the way that the timing of communicative acts changes with development. Crucially, we examine this in the context of both normal hearing (NH) children and children with hearing impairment (HI). Hearing impairment represents both a theoretically interesting perturbation of the communication system, and a potentially important application of this research given that language

interventions in this population often stress parental communication style. We thus start by discussing the theoretical problems of predictability and coordination, followed by a brief overview of relevant aspects of hearing impairment. We then turn to our longitudinal study of coordination.

Predictability

A wealth of work in this domain has established that infants are highly sensitive to the predictability of caregivers' inputs. For this purpose, such sensitivity is typically defined in terms of whether or not the parent responds at all to a child's communicative act (or vice versa). For example, in perturbation paradigms, the natural contingencies of interaction are disrupted by temporarily suspending interaction, as in still-face paradigms (Toda & Fogel, 1993), introducing transmission delays between mothers and infants interacting through remote video (Henning & Striano, 2011; Murray & Trevarthen, 1986; Striano, Henning, & Stahl, 2006), or surreptitiously manipulating the feedback mothers receive from their infants (Smith & Trainor, 2008). These studies show that infants are highly sensitive to the predictability of the caregiver's response from their own, and coordinate their behavior with their caregiver by 2 months of age (Crown, Feldstein, Jasnow, Beebe, & Jaffe, 2002; Jaffe et al., 2001). However, the continuous developmental changes in such sensitivities requires further investigation.

There are also studies showing that caregivers are highly sensitive to whether or not infants are responding contingently. For example, Smith and Trainor (2008) found that brief periods of non-contingent responding by infants (manipulated via a close-circuit video system) led caregivers to raise the pitch of their speech (presumably to reengage the infants). However, some asymmetry has been observed in mothers' and infants' sensitivity (or responses) to contingency. Whereas infants can distinguish between live video and delayed video of their mothers, mothers in contrast are less sensitive to delays (Striano et al., 2006). This is likely due the increased variability in the timing of infant behavior (Van Egeren, Barratt, & Roach, 2001), which may lead mothers to tolerate greater perturbations before discounting the contingent nature of their infants behavior (Henning & Striano, 2011).

As a whole, this work suggests even very young infants expect caregivers (and presumably other adults) to respond contingently to the infant's communicative acts. However, it does not address the temporal coordination between acts that must occur for successful communication. This leaves open crucial questions, such as how long of a delay "counts" as a contingent response, and more importantly, how capable is the child of responding contingently in a closely time-locked way, and how does this real-time coordination develop?

Coordination

To highlight the problems of coordination and synchronization, consider a simplified vocal conversation (ignoring facial expression, gesture, and other actions). Here, the critical problem is *when* does each partner respond, relative to the other? This is not a trivial problem, given that gaps in conversations are small in ways that simultaneously attempt to

minimize both the amount of silence and the quantity of overlapping talk (Stivers et al., 2009). Detecting that a partner is finished, and planning one's own utterance takes time and careful coordination (Levinson & Torreira, 2015). Consequently, a critical marker of coordination is how rapidly the infant responds after an utterance by the caregiver, and the variability of this response across conversational turns. One might then predict that over development, infants should become both faster and less variable in their responses.

An equally important question is what happens to these markers in a fully developed caregiver when they are confronted with the likely delayed and/or more variable responding of the infant or child? As adult coordination abilities are presumably mature, there is no obvious reason for the timing or its variability to change over time (as shown by Hilbrink, Gattis, & Levinson, 2015). However, one might also predict a change such that parents match their younger infants and respond more slowly initially (than they would to an adult), and decrease their latency with age. For example, recent work has shown that young children's ability to predict the turn-taking structure of interaction continues to develop through the preschool years (Casillas & Frank, 2017).

Parental latency matching may reflect a form of scaffolding, as caregivers tune into the developmental state of the child. In this case, caregivers may match the child, while simultaneously "leading by example," responding to their children at slightly shorter, moderately challenging latencies and shortening their latencies as the child develops. Alternatively, it could reflect parents' uncertainty about when the child is finished vocalizing (parents need to learn their child's cues). Thus, at early periods in development, when cues are more ambiguous (and parents are not as sensitive to them) one may predict slower and more variable responding, which is reduced as children's communication becomes clearer and parents learn their own child's cues. Under either model, change in the caregiver is driven at least in part by changes in the child. Consequently, one would predict not only a decrease in response time by caregivers, but also a close correlation between the response time profiles of individual mothers and individual children.

The goal of this study was to examine how the timing of responses between mothers and their children changes as a function of the child's age and hearing status. We employed a longitudinal design to examine potential parallels between the developmental changes in maternal and child responses.

Hearing Impairment

Childhood hearing impairment has the potential to perturb this developing system in multiple ways and poses significant challenges to children's communicative development. While in recent years there have been significant changes in the care and support provided for children with hearing loss, hearing loss remains an impediment to oral language and communicative development. For example, universal newborn hearing screening has led to the early identification of hearing loss and significantly improved language outcomes in these children (Moeller, 2000; Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998). Further, continual improvement of hearing aids and cochlear implants has greatly enhanced remediation efforts and speech and language outcomes for children with hearing loss.

Contemporary children with hearing loss are very different from previous cohorts in many ways, including in the nature of their interactions with caregivers (Ambrose, VanDam, & Moeller, 2014; Ambrose, Walker, Unflat-Berry, Oleson, & Moeller, 2015; VanDam, Ambrose, & Moeller, 2012). Nonetheless, despite these advances, hearing loss represents a significant long-term perturbation to this developmental system (Dunn et al., 2014; Tomblin et al., 2015).

It is unclear how communicative coordination (specifically the temporal synchrony) is affected by hearing loss. However, there is evidence that hearing loss has an impact on the nature and content of communicative interactions. Research on mother-child interaction in earlier cohorts of children found that mothers of hearing-impaired children were less likely to use verbal praise, were less likely to ask questions, and in general used more antagonistic speech (Goss, 1970). Subsequent studies found that mothers adopt a more dominant and directive interactive style (Wedell-Monnig & Lumley, 1980). Thus, hearing loss affects the history and nature of infants' experience with contingent caregiver interactions. While this work has emphasized the content of dyadic communication among for children with hearing loss, it is unclear at a basic level if the capacity for synchronous and coordinated communication is affected by this perturbation. One might predict from these examinations of the content, that maternal speech to children with hearing impairment is similarly less sensitive with more variable latencies, and less coordination with the child's own communicative dynamics.

Here we examined hearing loss as a potential perturbation for two reasons. First, it is a somewhat discrete perturbation to communicative development, and arbitrary in the sense that the presence of hearing loss in a child is highly unlikely to be related to the caregivers' communicative competence or coordination timing. Thus, it represents a quasi-experimental perturbation. Second, there are clear applied reasons as well. Understanding communicative development in this population may improve intervention, which in infancy often focuses on parent communicative style and content.

The present study

The current study examined communicative coordination longitudinally in a group of infants followed from roughly 4 months to 60 months. A large number of repeated measures on communicative timing in free conversation were collected both within and across multiple ages. A number of studies have examined the temporal properties of mother-child interaction using a longitudinal design, though these studies have either focused on the infancy period (Gratier et al., 2015; Harder, Lange, Hansen, Væver, & Køppe, 2015; Hilbrink et al., 2015) or preschool period (Casillas & Frank, 2017). In contrast, present study tracks infants over several years, which allows us to examine long-term developmental changes within individual mother-child dyads.

Previous research has examined mother-child interaction by examining dialogue in terms of discrete conversational turns (Jaffe & Feldstein, 1970; Stern, Jaffe, Beebe, & Bennett, 1975), or using time-series analyses to examine bidirectional influences on the presence or absence

of contingent behaviors within a given time windows (Cohn & Tronick, 1988; Jaffe et al., 2001; Keller et al., 2008). These focus on the question of predictability described above.

In contrast, the present study focused on the continuous development of coordination dynamics, with an alternative analytic approach that examines mother-child dialogue using more graded and fine-grained temporal measures of the timing of vocal responses. This study provides an extension of a recent longitudinal study of 3- to 18-month olds by Hilbrink et al. (2015), who observed age-related changes in the timing of infant responses. These methods are sensitive to millisecond-level changes in the timing of mother-child interaction over the course of development and reveal a number of age-related and dyad-related effects. In this regard, raw temporal measures, such as response latency, are particularly well suited for the analysis of interaction across disparate developmental time points because they can be calculated and applied similarly to young infants and older children despite differences in their developing linguistic and behavioral repertoire (e.g., the linguistic content of what is being said). Furthermore, these continuous temporal measures also permit the examination of variability in response latency, which has not been examined in detail, as well as communality analyses that examine the influence of mothers' response latencies on those of their children, and vice versa.

Half of the participants in this study were normal hearing (NH), and half had hearing impairment. The critical developmental questions were

- 1) *Does coordinative competence (latency and variability) in the child change over time, and over what developmental period is change observed?* It was expected that we would observe such changes as children improve their communicative abilities (Casillas & Frank, 2017; Kail, 1991; Keitel, Prinz, Friederici, Hofsten, & Daum, 2013), but the developmental period has not been fully identified.
- 2) *Is change also observed in the caregiver during this period?* Since much of the research in this area has focused on age-related changes in the child's responses, less is known about how caregivers may change as a function of their child's development, or whether their high level of competence makes them less inclined to change (Hilbrink et al., 2015). If change is observed, this could reflect learning as parents become better able to interpret their children's own cues, or even learning on the part of the child as the child learns to signal better when their turn is done. Perhaps more interestingly, it could reflect a form of scaffolding as parents tune their "input" to the abilities of the child.
- 3) *How does a child's latency and variability compare to the mother's?* Are mothers quicker and less variable at responding than children? These effects would reflect overall differences in the level of competence between mothers and children. Critically, are these differences maintained over development? If so, it could imply a form of scaffolding.
- 4) *Are changes in response latency and variability in the child (over development) aligned to that of the caregiver over and above their mutual changes with age?* If an effect of caregiver latency is found over and above that of age, this would suggest that children are tuning into the particular conversational dynamics of

the caregiver, that is they are learning appropriate communicative timing from their input.

- 5) *Are latency and variability in the caregiver aligned to the child over and above their mutual changes with age?* Such an effect would suggest that parental changes are not simply a parallel improvement in skill, but rather reflect a close attunement to the child's own ability. Coupled with a positive answer to #3 and 4 this would support a scaffolding or zone-of-proximal-development hypothesis (Vygotsky, 1978).

These questions have not been addressed by prior work, and answering them is crucial for understanding how this complex competence develops. These questions concern typical development, but this study also examined hearing impairment of some form. We did not attempt to match level or degree of hearing loss, nor did we control remediation type (a hearing aid vs. cochlear implant). This was because our goal was to examine hearing loss more generally as a perturbation to the developing system not to attempt (in our fairly small sample) a precise picture of any one form of hearing loss. This led to a final research question:

- 6) *Are any of the developmental effects identified in 1–4 moderated by hearing loss?* If so, this would suggest either that the level of coordination exhibited by caregivers (potentially as a form of scaffolding) is affected by their child's ability to perceive their utterances, or that the child's ability to tune into the input offered by the caregiver is moderated by hearing.

Method

Participants

Sixteen mother-child dyads were recruited as part of a previous longitudinal study of speech and language development in children (Moeller, Hoover, Putman, Arbataitis, Bohnenkamp, Peterson, Lewis, et al., 2007a; Moeller, Hoover, Putman, Arbataitis, Bohnenkamp, Peterson, Wood, et al., 2007b). In eight dyads, the child (5 male, 3 female) had normal hearing (NH). In the other eight, the child (2 male, 6 female) had hearing impairment (HI). After initial identification, all HI children received a hearing aid. While those with less severe hearing loss continued to use hearing aids (HA, $n = 3$), those with more profound hearing loss later received cochlear implants (CI, $n = 5$) between 12 and 27 months of age ($M = 17.5$ months).

Table 1 provides demographic information about the families, including the highest level of maternal education attained, as well Hollingshead Index of Social Status (Hollingshead, 1975). By these measures, there was little variability in SES, and all children were from middle class backgrounds. Speech and language development measures are also shown. The onset of canonical babbling was defined by the reliable production of well formed consonant-vowel syllables (Oller, 2000), previously reported for a subset of these children by Moeller et al (2007b). The Peabody Picture Vocabulary Test -III (PPVTIII) was administered at 42 months of age, and the Preschool Language Scale (version 3 or 4) was administered at 48–50 months of age. All of the NH children and four of the eight HI children achieved typical levels of language development (standard score > 85) by 42–48

months, according to the PLS/PPVT measures. Another two children (HI3 & HI4) achieved typical language by one measure but not the other.

At enrollment in the study, all children met early motor and cognitive landmarks according to parental report, and repeated observation of children's play skills over the course of the study confirmed that they were developing typically. Furthermore, children in the HI group were assessed for developmental milestones in domains other than communication (e.g., fine and gross motor, cognitive) by their early intervention professionals and/or in the laboratory using parent report checklists. No general developmental concerns were reported. Child HI2, did experience some early oral motor challenges that affected his speech clarity, but these resolved during the recording period.

The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from parents, for their own participation and for their children's participation, before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at Boys Town National Research Hospital.

Procedure

Temporal measures were derived from recordings of mother-child dialogue, obtained at a series of child ages (4, 5.5, 8.5, 10, 12, 14, 16, 18, 19/20, 21/22, 24, 30, 32, 36, 48, and 60 months). During recording, mothers were asked to interact freely with their children to elicit speech in a laboratory playroom containing a variety of toys. A total of 4,420 minutes of interaction were collected. This contained 20,120 maternal utterances and 20,126 child utterances. These recordings ranged in duration from 2 minutes to 55 minutes (Mean = 23.5 minutes, SD = 8.41), and included an average of 302 maternal and 178 child utterances per interaction.

Mother-child interactions were recorded on mini-DV videotapes with audio obtained from a Shure Model LX1-V microphone held in a fitted vest worn by the child. The audio track (16 bit, 32 kHz) was extracted from the videos and imported into Praat (Boersma & Weenick, 2010) for analysis. Mothers' and children's speech was coded in separate tiers. Coders identified individual utterances and utterance boundaries first through listening, and then through a fine-grained visual inspection of the waveform. The temporal locations of utterance boundaries were reviewed and confirmed by a second coder. Only utterances that were classified as non-vegetative (i.e., not a cough, sneeze, burp, etc.) by both coders were included in this analysis.

This manual temporal coding was laborious, but provided more fine-grained temporal information than automated methods using larger sampling intervals. Mothers' response latencies were calculated by determining the time interval between the end of the child's utterance and the beginning of the mother's utterance. Children's latencies were calculated in a similar way. Mothers' utterances that did not immediately follow a child's utterance, and children's utterances that did not immediately follow a maternal utterance, were not considered responses and were therefore not included in the analysis. Since latency values greater than 5 sec are unlikely to reflect contingent responses (Van Egeren et al., 2001), and

values below 0 sec reflect interruptions, the analysis included only utterances with latencies in the 0–5 sec range. For children, this restriction comprised 77.1% of the utterances (15,513 of 20,126), for caregivers constituted 79.4% of utterances (15,974 of 20,120).

Results

Data analysis adopted the following general approach. First, children's and mothers' responses were analyzed independently to examine age-related changes in the latency and variability of responses (Questions 1, 2). Second, dyadic analyses compared children's responses latencies to that of their mothers (Question 3) as a function of age. Third, we examined age-related changes in response latency to determine whether individual children's latencies (and the developmental trends in these latencies) were correlated with those of their mothers, over and above these general developmental changes (Questions 4, 5). The effects of the child's hearing status (Question 6) were evaluated within each of these analyses/sections.

Analysis of Child Responses

Mean latencies were calculated for each mother-child dyad at each age tested, and are shown in Figure 1.

As a preliminary analysis, mean latencies for individual children were regressed on child age for each child. Age accounted for a substantial portion of the variance in response latency (mean $R^2 = .37$), with similar values for NH (mean $R^2 = .31$) and HI (mean $R^2 = .43$) dyads. Children's latencies decreased as a function of age in all dyads, with an average slope of -18 ms per month of age. A one-sample t -test confirmed that this average slope was significantly lower than 0, $t(15) = -8.52$, $p < .00001$. Neither the slopes, $F(1,14) = 0.27$, $p = .61$, nor intercepts, $F(1,14) = 0.22$, $p = .64$, differed significantly as a function of hearing status.

We next examined the variability in children's responses, by regressing the standard deviation in latency on age for each child. Again, child age accounted for a substantial portion of the variance in response latency (mean $R^2 = .40$), with stronger relationship (on average) for HI (mean $R^2 = .49$) than NH children (mean $R^2 = .31$). A one-sample t -test confirmed that the average slope of these regressions (-11 ms/mo) was significantly lower than 0, $t(15) = -7.36$, $p < .00001$. This demonstrated that children's responses became less variable with age. Neither the slopes, $F(1,14) = 0.23$, $p = .64$, nor intercepts, $F(1,14) = 0.09$, $p = .77$, differed significantly across hearing status groups.

These descriptive results were validated in a linear mixed-effects (LME) model which combined data from all subjects. An LME approach is particularly useful for the analysis of longitudinal datasets since it provides an appropriate accounting of the error variance related to repeated measurement of individual dyads, and can handle unbalanced datasets (e.g., measurements at different periods for different children). Analyses were carried out using the LME4 package (Bates & Sarker, 2011 version 1.1-12) in R (version 3.3.2). Significance of the fixed effects was evaluated using the t statistic and the Satterthwaite (1978) approximation for degrees of freedom as implemented in the lmerTest package (Kuznetsova, Brockoff, & Christensen, 2016, Version 2.0-33)

Models had two fixed effects. Hearing status was sum coded (NH = $-.5$, HI = $+.5$), and child age was centered at the grand mean. In order to determine the most appropriate random effects structure, we held the fixed effects constant and compared a model with only random intercepts for dyad, to one with a random slope of age on dyad (c.f. Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017). We adopted the simpler model with only random intercepts as the model with a random slope did not show a significant improvement in fit, $\chi^2(2) = 1.13$, $p = .57$. The absolute performance of the model was evaluated using procedures described by Long (2012, pp. 427–429) in which the observed data were correlated with fitted values based on the fixed effects alone, producing a value of $R^2 = .30$.

This model found a significant effect of child age, with children's responses coming roughly 15 ms earlier with each passing month, $B = -15.45$, $SE = 1.75$, $t(177.83) = -8.81$, $p < .0001$. There was no significant main effect of hearing status, $B = -23.22$, $SE = 62.03$, $t(15.73) = -.374$, $p = .71$, nor an age $\times$ hearing status interaction, $B = 2.24$, $SE = 3.51$, $t(177.83) = 0.64$, $p = .53$.

For the purpose of replicating a recent study by Hibrink et al. (2015), who observed *increases* in latency between 3 and 9 months of age, the data were reanalyzed using only a subset of data for child-ages of 9 months or less. In this case we too observed a significant increase in latency, $B = 65.59$, $SE = 30.18$, $t(30.18) = 2.17$, $p = .04$. Altogether, this analysis demonstrates an overall decrease in latency from infancy to childhood, with a brief temporary increase around 9 months of age. No significant main effect or interaction effect of hearing status was found. An examination of regression coefficients for individual children for whom sufficient data was available to calculate slopes during this time period found that 6/8 NH children and 3/3 HI children showed positive slopes during this period. The magnitude of the slope was not significantly correlated with the age of babble onset, $r = .10$.

As above, a similar analysis was carried out examining variability (SD) in the latency of children's responses at each age. Based on fixed effects alone, the model produced a value $R^2 = 0.34$. In this model, the effect of age was significant, with children's response latencies becoming less variable as a function of age, $B = -9.44$, $SE = 0.98$, $t(178.1) = -9.597$, $p < .0001$. The effect of hearing status was not significant, $B = -25.16$, $SE = 34.93$, $t(16.24) = -0.720$, $p = .48$, nor was the interaction of age $\times$ hearing Status, $B = -1.65$, $SE = 1.97$, $t(178.1) = -0.840$, $p = .40$.

Thus overall, we observed a decreased in both latency and variability over development, with a brief uptick at 9 months. This was not moderated by hearing status.

Analysis of Maternal Responses

Mothers' responses to children's utterances were analyzed using the same statistical procedures as described above. Mean latencies were calculated for each mother-child dyad at each child-age tested, and are shown in Figure 1. A preliminary analysis of developmental changes in maternal responsiveness was done by regressing mother's mean latency on child's age individually for each dyad. Child-age accounted for roughly half of the variance in mean maternal response latency (across subjects, mean $R^2 = .51$), which was similar

between normal hearing (mean $R^2 = .49$) and hearing impaired (mean $R^2 = .53$) dyads. These effect sizes were larger than that observed for child responses.

As with children, a negative slope was observed across all caregivers, reflecting mothers' increasingly quicker responses as their children developed. A one-sample t -test found that the average slope ($M = -19$ ms per month of child-age) was significantly lower than zero, $t(15) = -8.43$, $p < .00001$. The slopes did not differ significantly between hearing groups, $F(1,14) = 1.99$, $p = .18$, nor did the intercepts, $F(1,14) = 0.71$, $p = .42$.

The variability of mothers' responses was examined by calculating the SD of latency for maternal responses at each child-age. These were then entered into linear regressions predicting maternal variability from child-age (separate regressions for each dyad). The average slope of these regressions was -11 ms/month, illustrating that the timing of maternal responses became less variable for older children. A one-sample t -test confirmed this effect, showing that the average slope was significantly lower than zero, $t(15) = -6.84$, $p < .00001$. Neither the average slope, $F(1,14) = 0.22$, $p = .65$, nor the average intercept, $F(1,14) = 1.35$, $p = .26$, differed significantly across hearing status groups. Across all dyads these regressions produced an average R^2 value of 0.38, which was similar between normal hearing (mean $R^2 = .31$) and hearing impaired (mean $R^2 = .44$) dyads.

For our primary analysis of maternal responses, similar LME models were constructed with the same fixed effects as for the child models. As before, we compared models with and without random slopes for child-age, and found that the introduction of random slopes did not significantly increase fit of model, $\chi^2(2) = 2.03$, $p = .36$. Thus a model with only random intercepts was adopted. On the basis of fixed effects alone, the model fit observed data at a level of $R^2 = .39$, suggesting similarly strong effects as in the child model.

In this model, child-age was significant, with mothers responding roughly 17 ms faster with each month of child-age, $B = -17.27$, $SE = 1.49$, $t(174.80) = -11.63$, $p < .0001$. The effect of hearing status was not significant, $B = 3.17$, $SE = 78.92$, $t(16.44) = .04$, $p = .97$, nor was the interaction of age $\times$ hearing status, $B = 4.53$, $SE = 2.97$, $t(174.80) = 1.52$, $p = .13$. Thus, this model confirms a dramatic drop in latency with age suggesting some attunement to the developmental state of the child. Intriguingly, this did not appear to differ as a function of the perturbation afforded by hearing impairment, despite evidence that maternal interactions differ in other ways for mothers of children with hearing impairment.

A similar analysis was carried out examining the variability (SD) in the latency of mothers' responses. Based on fixed effects alone, the model produced a value of $R^2 = 0.27$. In this model, child-age was significant, with mothers' response latencies becoming less variable as a function of child-age, $B = -10.04$, $SE = 1.17$, $t(176.54) = -8.56$, $p < .0001$. The effect of hearing status was not significant, $B = 56.22$, $SE = 49.71$, $t(16.57) = 1.13$, $p = .27$, nor was the interaction of age $\times$ hearing status, $B = -2.04$, $SE = 2.35$, $t(176.54) = -0.868$, $p = .39$. This suggests a strong developmental effect on both latency and variability in the caregiver. However, there was little difference as a function of hearing status.

Comparison of maternal and child latency over development

The preceding analyses show clear evidence of analogous changes in latency and variability over development in children and their mothers. We next sought to compare this more directly, both to determine if one or the other is responding systematically faster (or with lower variance) and to determine if the rate of change differed between the group.

To examine this question we compared the mean and variability of mothers' and children's responses to determine potential differences. Mean child and maternal latencies were combined into a single dataset. An LME model, with random intercepts for dyad, was constructed with factors of age (centered), and talker (mother = +.5, child = -.5). As expected, a significant effect of age was found, $B = -16.3$, $SE = 1.1$, $t(364.90) = -14.00$, $p < .0001$, corresponding to the results above in which mothers and children were analyzed separately. A significant effect of talker was found, $B = -264.7$, $SE = 30.8$, $t(355.20) = -8.60$, $p < .0001$, with mothers ($M = 1,003$ ms) responding an average of 265 ms quicker than their children ($M = 1,268$ ms), across all ages. The interaction of age $\times$ talker was not significant, $B = -1.8$, $SE = 2.2$, $t(355.20) = -0.78$, $p = .44$. This suggests that the mother-child latency difference was maintained throughout development. Finally, when hearing status was added to the model, it did not have a significant effect ($B = 8.1$, $SE = 65.8$, $t(143.0) = 0.123$, $p = .90$), it did not interact significantly with any of the other factors (all $p > .13$), and did not significantly improve the overall fit of the model, $\chi^2(4) = 3.05$, $p = .55$.

This analysis was repeated using the variability (SD) of responses as the dependent measure. As expected, a significant effect of age was found, $B = -9.6$, $SE = 0.8$, $t(365.2) = -12.54$, $p < .0001$, with mothers and children's response latencies becoming less variable as a function of child age. As significant effect of talker was found, $B = -92.6$, $SE = 20.3$, $t(355.1) = -4.57$, $p < .0001$, with mothers (mean SD = 1,005 ms) being less variable than their children (mean SD = 1,095 ms). The interaction of age $\times$ talker was not significant, $B = -0.3$, $SE = 0.001$, $t(355.1) = -0.21$, $p = .84$, suggesting that the mother-child variability difference is maintained over development. When hearing status was added to the model, it did not have a significant main effect, $B = -16.0$, $SE = 42.3$, $t(14.2) = -0.378$, $p = .71$, and did not significantly improve the overall fit of the model, $\chi^2(4) = 5.83$, $p = .21$. However, hearing status did interact significantly with talker, $B = -84.6$, $SE = 4.13$, $t(352.1) = -2.05$, $p = .04$. While the response latency variability was similar for mothers of NH children (mean SD = 997 ms) and HI children (mean SD = 1,008 ms), NH children's variability (mean SD = 1,126 ms) was slightly greater than that of HI children (mean SD = 1,056 ms).

Thus, we replicate the prior decrease in latency and variability over development, and document that mothers respond faster and less variably than their child (across all ages and for both hearing groups).

Relationship of Child Latency to Maternal Latency

The preceding analyses showed that as children age they respond more quickly to their mothers and their mothers respond more quickly to them. These trends persist into the preschool years. These analyses clearly identify parallel developmental trends, but they do not address whether there may be bidirectional dyadic influences. Are mothers and their

children simply responding more quickly as they get older, or are mothers and children influenced by each other?

To address this question, we examined the relation between mothers' and children's responses in two different ways. The first involved computing the correlation between individual dyad mothers' mean latencies and their children's latencies across ages (r values are shown within each panel in Figure 1). In this analysis, strong correlations occur when the mother and child show similar patterns of change in response latency over the course of development. The average correlation across all dyads was $r = .62$, which demonstrates an overall relation between developmental patterns for mothers and their children. However, the pattern of correlations did appear to be affected somewhat by hearing status, with higher average correlations for NH dyads ($r = .70$) than for HI dyads ($r = .54$). Differences were also apparent in the variability in the strength of correlations across dyads within each hearing status group (Figure 2). The relationships between mothers' and children's latencies were more variable in the dyads with hearing impaired children, while correlations within dyads with normal hearing children are consistently higher and less variable.

In an attempt to account for the variability observed in HI dyads, the correlation coefficients were themselves correlated with language measures for the child shown in Table 1. The motivation for this was to test the hypothesis that children with ultimately stronger language skills might show tighter temporal coordination with their mothers. However, no significant correlations were found. For vocabulary (PPVT) at 42 months: $r = .16$ for all dyads, $r = -.17$ for HI dyads. For our omnibus language measure (PLS-3/4) at 48–50 months: $r = .27$ for all dyads, $r = .07$ for HI dyads.

Our second way of examining the relationship between mothers' and children's responses was to examine correlations between the age-related slopes for mothers and their children. These slopes are depicted as pairs of regression lines within each subplot in Figure 1. This allows us to ask whether the amount of change in a mother (over months of child age) is related to the amount of change in the child. Figure 3 shows the coefficients for the slopes of these regression lines for mothers and children, in both the normal hearing and hearing impaired groups. Positive correlations in both groups show that mothers with steeper age-related changes in response latency have children with steeper changes. The correlation between mothers' and children's slopes is somewhat greater for normal hearing dyads, $r = .85$, than for hearing impaired dyads, $r = .60$.

These clearly document a relationship between the mother's and child's behavior. However, such changes could be the result of an underlying change over age in both groups, without necessitating a tight coupling on a month-by-month basis. Thus, for a more comprehensive analysis, we developed a series of LME models in which mother's latency was introduced as an additional predictor of child latency, and vice versa. These were used to conduct a form of communality analysis. Here the question is whether maternal latency predicts child latency over and above the effect of age (and vice versa). If such an effect is found it would suggest that children are not just getting faster as they age, but that they are specifically attuning to input of the parent on a month-by-month basis. As above, the random effects structure of these models included random intercepts, but not random slopes.

We started with a model that had a single predictors of child latency--child-age—and random intercepts of dyad. Next, we added maternal latency and compared it to the initial baseline individual models. This model outperformed the simpler model with only child's age, $\chi^2(2) = 44.60, p < .0001$, suggesting that maternal latency is a unique predictor of child latency – over and above the child's age. In this model, maternal latency was significant and positive predictor, $B = 553.2, SE = 87.8, t(143.02) = 6.30, p < .0001$, suggesting an effect of maternal latency that cannot be attributed to age. The interaction was not significant, $B = 4.6, SE = 5.8, t(182.75) = 0.80, p = .43$, suggesting that this coupling did not change with age. Next, in a third model we added hearing status and its interaction with child-age and maternal latency as fixed effects. This did not significantly improve the overall fit, $\chi^2(4) = 7.80, p = .10$. Nonetheless, there was a significant effect of hearing status, $B = -394.0, SE = 170.7, t(101.05) = -2.31, p = .02$, as well as a significant interaction effect of hearing status $\times$ mother's latency, $B = 436.9, SE = 176.3, t(136.66) = 2.48, p = .014$. These results suggest that while HI children were slower to respond overall than NH children, the effect of hearing status was modulated by their mothers' timing (which perhaps explain our inability to detect any moderation of the slope by hearing ability in earlier, simpler analyses). An alternative interpretation is that children's latency is related to their mothers' latency, but that the relation is affected by hearing loss.

This communality approach was then used to examine response variability. Again, we started with a model containing only child age. When we added maternal variability as a predictor, this model significantly outperformed the baseline model, $\chi^2(2) = 28.95, p < .0001$. In this model, the main effect of maternal latency was significant, $B = 333.2, SE = 60.4, t(163.03) = 5.51, p < .001$, showing a tight coupling between caregivers and children that cannot be accounted for by parallel development. The interaction of maternal variability and child-age, was not significant, $B = 4.6, SE = 4.1, t(182.83) = 1.1.12, p = .26$, suggesting this coupling is maintained over development. The addition of hearing status as a factor did not significantly improve the fit of the model, $\chi^2(4) = 5.43, p = .25$, and was not a significant predictor, $B = -106.5, SE = 123.7, t(125.2) = -0.861, p = .39$.

The data were then analyzed using a similar approach, but with the mother's latency as the dependent measure. Again, we started with a model that included child age as the only predictor of maternal latency. This was compared to a model adding child latency as a fixed effect. This model significantly outperformed the simpler models with only child-age as a predictor, $\chi^2(2) = 47.59, p < .0001$. In this model, the main effect of child latency was significant and positive, $B = 322.0, SE = 67.5, t(178.18) = 4.77, p < .0001$, suggesting again a tight coupling between child and maternal latency that cannot be attributed to age. The interaction of child latency $\times$ child age, was marginally significant, $B = -9.5, SE = 4.9, t(171.25) = -1.96, p = .052$. Overall, this model suggests a tight coupling between maternal and child latency that cannot be accounted for by mere parallel development. Next, we added hearing status and its interaction with latency and age as additional fixed effects. Hearing status did not significantly improve the fit of the model over and above the model with child-latency and age, $\chi^2(4) = 5.13, p = .27$. Similarly, in this model, the effect of hearing status was not significant, $B = -300.5, SE = 182.0, t(145.50) = -1.65, p = .10$, suggesting that mothers' overall latencies did not vary across hearing status groups. The interaction of hearing status $\times$ age was also not significant, $B = -18.0, SE = 11.9, t(170.57) = -1.52, p = .06$.

13), suggesting that the age-related changes in mothers' response latency did not vary across hearing status groups. However, the interaction of hearing status $\times$ child latency was marginally significant, $B = 265.2$, $SE = 139.8$, $t(175.86) = 1.90$, $p = .06$, suggesting that NH children's latencies may influence their mothers' latencies differently than did those of HI children.

Finally, an analogous analysis was conducted using *maternal response variability* as the dependent measure. Here, the model adding child response variability (and the interaction) to the baseline model with only child age significantly outperformed both baseline model, $\chi^2(2) = 25.77$, $p < .0001$. In this model there was a main effect of child response variability $B = 432.1$, $SE = 83.7$, $t(182.79) = 5.16$, $p < .0001$, but the interaction of child variability and child-age was not significant, $B = 2.1$, $SE = 5.6$, $t(178.18) = -0.36$, $p < .72$. In a third model the addition of hearing status as a factor did not significantly improve the fit of the model, $\chi^2(4) = 5.10$, $p = .287$, and was not a significant predictor individually, $B = -283.7$, $SE = 192.5$, $t(173.25) = -1.47$, $p = .14$, or in interaction with other factors.

In sum, across these four analyses, we observed a unique effect of the dyadic partner's latency and variability over and above age. Children and caregivers are tightly coupled in both how quickly they respond (from month to month) and the variability by which they do so.

Discussion

This study revealed a number of key trends. First, children's response latencies are both shorter and less variable with increasing age. Second, mothers' latencies also show decreases in mean and variability with child age. Third, neither of these trends grossly differs for dyads in which the child had hearing loss. Fourth, mothers' responses are typically shorter and less variable than their children, and this difference is maintained throughout development. Fifth, there was a close coordination between mothers and children both in the overall latencies and variability of responding, and in the way that these change over time. Finally, this coordination was not a mere consequence of the fact that both participants in a dyad are changing over time. On a month-by-month basis, maternal latency was a unique predictor of child latency, over and above child age, suggesting that children are to some extent acquiring the coordination dynamics of their mother. Perhaps even more intriguingly, child latency was a unique predictor of *maternal latency* over and above age – mothers are also matching the dynamics of their children.

Our finding of shorter latencies for maternal responses, compared to child responses, corresponds to previous studies with infants (Beebe, Alson, Jaffe, Feldstein, & Crown, 1988; Casillas, Bobb, & Clark, 2016; Hilbrink et al., 2015; Jasnow & Feldstein, 1986), but extends this work to demonstrate the persistence of this effect through early childhood. Our longitudinal design, coupled with millisecond-level coding of responses, provides a novel view of the age-related changes in both child and maternal responses. While previous work (Hilbrink et al., 2015) examining the infant period (3–18 months) did not observe infant-age related effects on maternal response latencies, the present study finds significant decreases in response latency extending through childhood.

Our analysis of child latencies, showed overall decreases in response latencies between 4 and 60 months of age, with a temporary increase in latency around 9 months (replicating Hilbrink et al., 2015). It has been argued that the capacity for coordinating interactional timing exist in early infancy in a prelinguistic form (Jasnow & Feldstein, 1986; Rochat et al., 1999), and that the increase in latency reflects the infants' integration of their new linguistic skills with their "interaction engine" (Hilbrink et al., 2015; Levinson, 2006). While the present study did not examine the content of utterances, or the nature of the responses given, true communicative exchanges place demands on the developing child that are reflected in their response latencies. For example, recent work has shown that question complexity increases response latencies in young children (Casillas et al., 2016). Thus, these increasing latencies could reflect increasing demands on the child as they attempt to respond more communicatively. These demands are then lessened beyond 9 months as the child gains communicative skill.

Nonetheless, the broader trend was for a reduction in latency over child age. There are a number of reasons why we might have observed changes in the child and maternal latencies over time. As children become more linguistically proficient with age, the amount of time necessary to process and respond to mothers' utterances may be reduced (Casillas et al., 2016). Similarly, with age, children's speech productions become more intelligible allowing mothers to respond more quickly. Although these considerations might be at play to some degree, it is likely a mistake to characterize the temporal properties of mother-child dialogue exclusively in terms of processing speed limitations. Mothers' and children's goals are not simply defined in terms of bandwidth and the communication of the maximum information in the minimum amount of time. It is more likely that mothers and children incorporate considerable temporal slack in their dialogue, settling in on a rhythm in which their responses occur at more predictable time points within the dialogue as a whole. This temporal predictability may help guide attention to facilitate the processing of anticipated information (Jones & Boltz, 1989).

Previous studies have found mutual reciprocal influence between mothers and infants (Beebe et al., 1988; Jaffe et al., 2001; Jasnow & Feldstein, 1986), in terms of the predictability of timing within a test session. The present longitudinal study illustrates an additional dimension of this reciprocal influence at the level of age-related changes over the course of development. The finding that each participant's latency predicts the other *over and above* age suggests there is something more than simple developmental changes in each half of the dyad. This coordination of response latencies was demonstrated at the level of groups and at the level of individual mother-child dyads, and it was observed both in mean latency and in the variability of latencies within a month. How are the temporal parameters of this mother-child coordination negotiated over the course of development?

One possibility is that mothers initially follow their children's lead during infancy (slowing down the faster responses they would exhibit with adults) in order to scaffold the contingent nature of their interaction. Overall, children's response latencies were many times more variable than those of their mothers, which is consistent with other studies (Van Egeren et al., 2001), suggesting that their ability to coordinate their timing in dialogue might be immature. Mothers, on the other hand, were less variable in their timing than their children,

which may facilitate children's processing of speech by reducing temporal uncertainty. Further, the fact that maternal latency was closely time-locked to their child, but significantly faster, would seem to support this kind of scaffolding. Caregivers consistently exhibit timing that is slightly faster than the current state of the child (even as it changes), and this temporal coordination did not interact with age – it was maintained throughout the long developmental period studied. That is, they appear to be “leading” the child to appropriate timing, following something resembling a zone of proximal development. Though we lacked sufficient power to do this here, one way of addressing this issue in future work might be to examine time-lagged correlations between mothers' and children's responses, in which mothers' response latencies at time point A are entered as predictors of children's latencies at time point B.

Although our communality analysis shows that mutual influence between mothers' and children's latency in terms of mean and variance, one might expect that temporal coordination becomes more bidirectional over the course of development, as a function of the child's increasing conversational competence. Previous work demonstrated the prevalence and importance of contingent maternal responses for language development and learning in infants (Goldstein & Schwade, 2008; Gros-Louis et al., 2006; Nitttrouer, 2010; Northrup & Iverson, 2015).

The comparison of dialogue between mothers and their normal hearing and hearing impaired children affords the opportunity to examine the impact of potential perturbations of the communicative system. However, the group-level data failed to find significant main effects or interactions of hearing status (in terms of the overall developmental trends). This is, of course, positive news for hearing impaired children and their families because it suggests that the temporal properties of their dialogue are similar to those of normal hearing children.

However, at the level of individual dyads, mother-child correlations tend to be lower and more variable in the HI group. These correlations capture some aspects of the developmental change, but not others. For example, as shown in Figure 1, dyad HI2 had the lowest mother-child correlation ($r = .18$) of the entire sample, yet had the most similar regression coefficients for age. The slopes for the mother and child practically overlap, as do the mean latencies at 48 and 60 months, suggesting that they are a dyad in which the temporal coordination has become very tightly coupled. The lack of correlation may thus indicate less month-by-month coupling, even as at the more macro level there is considerable similarity in latency.

At the same time, however, our communality analysis that showed that the influence of mothers' response latency on the child's latency is moderated by hearing loss. This suggests that hearing loss may be responsible for subtle effects on the interactional coordination between HI children and their caregivers. This variability may itself be important in understanding language outcomes for children with hearing, particularly given the increased variability in language outcomes for children with hearing loss (Lederberg, Schick, & Spencer, 2013), and the importance of maternal sensitivity on language growth in children with cochlear implants (Quittner et al., 2013)

As a whole, these data support a relatively protracted period of learning during which children learn to respond more rapidly and consistently to communicative acts. Crucially during this time, mothers appear to closely align the timing of their own acts to the capacities of the child, perhaps as a way to scaffold or lead them to a mature level of communicative competence.

Acknowledgments

This work was supported by grants from the National Institutes of Health (P20GM109023, R03DC009884 awarded to NAS, and R01DC008089, P50DC000242 awarded to BM). We thank Mary Pat Moeller for support and encouragement in this project, in particular making the videos of the mother-child interaction (supported by R01DC006681) available to us for analysis. The authors declare no conflicts of interest.

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Figure 1.

Figure 2.

Figure 3.

Table 1

Participant characteristics for children in the hearing impaired (HI) and normal hearing (NH) group. Highest level of maternal education attained. SES: scores on the Hollingshead (1975) Index of Social Status. Age at which children demonstrated consistent canonically babbling. PPVTIII: Peabody Picture Vocabulary Test (standard score), PLS: Preschool Language Scale, (standard score, superscript refers to the version used in testing). Age in months at which hearing loss was identified. Age in months at which children first received a hearing aids, Age which children received a cochlear implant. For children who continued to use a hearing aid (HA) their better ear pure-tone average (PTA) threshold is given. Where “-” is shown, data were not available for that child.

Subject Code	Child Sex	Maternal Education	SES	Babble Onset (mo)	PPVT III	PLS	Age of ID (months)	Age at HA	Age at CI (mo)	Better Ear PTA (dB)
HI1	F	Some college	40	14	48	73 ⁴	2	3	27	
HI2	M	Assoc. Degree	54	14	82	66 ³	1	2		67
HI3	M	M.S.	18	18	91	83 ³	1	3	12	
HI4	F	Some college	44	-	84	103 ⁴	0	6		45
HI5	F	B.S.	15	-	94	104 ⁴	3	4	13	
HI6	F	B.A.	22	18	87	91 ³	9	10	16	
HI7	F	B.S.	29	20	109	100 ³	0	5	18	
HI8	F	B.S.	22	10	95	101 ⁴⁺	0	4		50
NH1	M	M.S.	22	10	122	-				
NH2	M	M.A	22	8.5	120	110 ³				
NH3	F	B.S.	47	8.5	104	110 ³				
NH4	M	B.A.	18	7	103	117 ³				
NH5	F	M.S.	40	7	102	129 ³				
NH6	M	M.A	18	7	109	111 ³				
NH7	F	MBA	18	8.5	106	108 ³				
NH8	M	B.S.	36	8.5	107	106 ³				

³ PLS-3⁴ PLS-4⁺ Score based on receptive portion of test only