Published in final edited form as:

Psychol Sci. 2014 July ; 25(7): 1314–1324. doi:10.1177/0956797614531023.

A social feedback loop for speech development and its reduction in autism

Anne S. Warlaumont,
University of California, Merced

Jeffrey A. Richards,
LENA Research Foundation

Jill Gilkerson, and
LENA Research foundation and University of Colorado at Boulder

D. Kimbrough Oller
University of Memphis and Konrad Lorenz Institute for Evolution and Cognition Research

Abstract

We analyze the microstructure of child-adult interaction during naturalistic, daylong, automatically labeled audio recordings (13,836 hours total) of children (8- to 48-month-olds) with and without autism. We find that adult responses are more likely when child vocalizations are speech-related. In turn, a child vocalization is more likely to be speech-related if the previous speech-related child vocalization received an immediate adult response. Taken together, these results are consistent with the idea that there is a social feedback loop between child and caregiver that promotes speech-language development. Although this feedback loop applies in both typical development and autism, children with autism produce proportionally fewer speech-related vocalizations and the responses they receive are less contingent on whether their vocalizations are speech-related. We argue that such differences will diminish the strength of the social feedback loop with cascading effects on speech development over time. Differences related to socioeconomic status are also reported.

Keywords

Social Interaction; Speech Development; Autism; Socioeconomic Status; Rewards

Introduction

Learning to produce vocalizations with speech-like acoustics is an essential component of early spoken language learning (Oller, 2000). Here we propose a positive social feedback

Corresponding author: Anne S. Warlaumont, Cognitive and Information Sciences, School of Social Sciences, Humanities, and Arts, University of California, Merced, 5200 North Lake Rd., Merced, CA 95343, awarlaumont2@ucmerced.edu, (607) 227-3726.

Author Contributions: A.S.W. designed the study with input from J.G., J.A.R, and D.K.O. J.G. and J.A.R. acquired the audio recordings and demographic information. A.S.W. and J.A.R. analyzed the data. A.S.W., D.K.O., and J.G. interpreted the results. A.S.W. wrote the paper and D.K.O., J.G., and J.A.R. contributed revisions. All authors approved the final version of the paper for submission.

loop supporting speech development (Fig. 1). When a child produces a sound containing speech or speech-related material, the child is more likely to receive an immediate, positive response from an adult than if the child sound did not contain speech or speech-related material. Receiving an immediate response encourages the subsequent production of similar utterances. These individual interactions accumulate over time, contributing to speech development over the course of days, months, and years. The proposal is in keeping with constructivist theories of cognitive development (Karmiloff-Smith, 1998; Leezenbaum et al., 2013): children's behaviors affect environmental input and atypicalities are expected to have cascading effects on later speech ability.

The social feedback loop is supported by experiments showing that when caregivers' responses are contingent on infant vocalizations being speech-related (non-cry, non-laugh, and non-vegetative) the result is more frequent speech-related child vocalizations (Goldstein, King, & West, 2003). Furthermore, when adults' contingent responses are vocal, children's future vocalizations acquire acoustic characteristics resembling the adults', such as more speech-likeness, more vowel resonance, or better consonant-vowel timing (Bloom, 1988; Goldstein & Schwade, 2008). Additionally, a mother's responsiveness to her child's communicative behaviors predicts language performance at a later age for both TD infants (e.g. Tamis-Lemonda, Bornstein, & Baumwell, 2001) and children with developmental disabilities (Yoder, 1999; Girolametto, 1988), and greater vocal coordination between infant and adult predicts later language, cognitive, and perceptual ability (Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Greenwood, Thiemann-Bourque, Walker, Buzhardt, & Gilkerson, 2010). Note that the learning mechanisms that utilize these contingencies needn't be explicit (Thompson-Schill, Ramscar, & Chrysikou, 2009).

This social feedback loop could potentially help our understanding not only of typical development but also of atypical development. We consider the case of autism spectrum disorder (ASD). Differences in both social interaction and speech development are central to ASD. For instance, ASD is associated with less social interaction, less frequent initiation of social interactions, and atypical turn taking patterns (American Psychiatric Association, 2000; Zwaigenbaum et al., 2005; Paul, Orlovski, Marcinko, & Volkmar 2009; Sheinkopf, Mundy, Oller, & Steffens, 2000; Dawson et al., 2004; Anderson et al., 2007; Warren et al., 2010). Children with or at high risk for ASD also tend to produce fewer speech-related vocalizations (Warren et al., 2010; Paul, Fuers, Ramsay, Chawarska, & Klin, 2011; Patten et al., 2014), and their vocalizations tend to be atypical (Sheinkopf et al., 2000; Oller et al., 2010; Peppé, McCann, Gibbon, O'Hare, & Rutherford, 2007; Paul et al., 2009, 2011; Sheinkopf, Iverson, Rinaldi, & Lester, 2012; Patten et al., 2014). Children with ASD also typically acquire language relatively slowly (Anderson et al., 2007).

Considering this proposed feedback loop may further our understanding of the relationship between social interaction and speech development in ASD. The disorder could affect the feedback loop in three ways. First, children with ASD might produce fewer vocalizations and/or fewer vocalizations that are speech-related. Second, caregivers of children with ASD might respond differently to their children's vocalizations. Third, children with ASD might differ in their ability to learn from adults' contingent responses.

Here we utilize daylong naturalistic recordings and automated labeling and analysis to look for evidence in moment-to-moment interactions of the proposed feedback loop. We first analyze data from TD children and ask (1) whether speech-related child vocalizations are more likely than non-speech-related child vocalizations to receive immediate adult responses and (2) whether a child vocalization is more likely to be speech-related if the child's previous speech-related vocalization received an immediate response. Next we assess the frequency of child speech-related vocalization and the patterns of child-caregiver vocal interaction in TD versus ASD. We then test whether the adult contingency on child and child contingency on adult predictions of the feedback loop hypothesis hold for ASD and test for differences in these two contingencies compared to TD.

Finally, we test for differences across age, maternal education level, and gender. We expect that as maternal education increases, child speech-related vocalization rate and child-adult interactivity will increase; we also expect both these to increase with age (Hart & Risley, 1995; Greenwood et al., 2010). We also test whether the two contingencies of the social feedback loop differ across SES and/or age.

Method

We used a subset of the recordings used in a previous study by Oller et al. (2010). The TD participants were 106 children (45% male) 8–48 mo. of age. The ASD participants were 77 children (83% male) 16–48 mo. of age diagnosed with the Autism subtype of ASD, except for the children who were too young for an Autism diagnosis so were categorized under Pervasive Developmental Disorder Not Otherwise Specified. 76 participants in the TD group were recruited from the Denver, Colorado area. The other TD and all the ASD participants were recruited from the broader USA. Both groups had a wide range of maternal education, used here as a proxy for SES, from some high school to graduate degree. More detail on recruitment, validation of diagnoses, etc. can be found in the Oller et al. (2010) Supporting Information.

Recordings were made and pre-processed using the LENA™ (Language ENvironment Analysis) system. A small device fit into custom clothing recorded the child's voice as well as other sounds in the child's environment. Parents were instructed to begin recording when the child awoke in the morning. All recordings lasted at least 12 hours and longer ones were truncated. Recordings took place in varied settings including in the home, car, preschool, and, for the ASD group, speech-language therapy. In total, 1,153 recordings, 13,836 hours, were included. The Essex Institutional Review Board approved the procedures. All analyses were also run on an alternative dataset (Warren et al., 2010) with very similar results (see *Alternative Dataset* Supplemental Material). In addition, a 426-recording subsample from the main dataset that was matched on gender, age, and SES was created and analyzed (see *Matched Subsample* Supplemental Material) to ensure that our primary findings were not affected by gender or SES imbalance between ASD and TD groups and to facilitate visualization and computational modeling.

The LENA software automatically segmented each recording by sound source (Oller et al., 2010). Figure 2 gives an example for a portion of one recording. Here we attend to only two sound sources: child wearing the recorder and adult. Within child segments, the system also identifies sub-segments of vocalization and labels them as speech-related (speech, non-word babble, and singing) or as non-speech-like (laughing, crying, burping, coughing, etc.). The *Segment Extraction* Supplemental Material gives more information.

Files containing the primary data analyzed in this study and scripts used to extract that data from the ITS files output by the LENA software are available in the Data And Scripts Supplemental Material. Questions about potential use of the LENA Research Foundation database beyond what is provided here should be directed to info@lenafoundation.org.

Results

Typically developing group

Speech-related vocalization rate—Figure 3 shows the relative frequency of child speech-related vocalization in each recording. The TD group's recordings contained greater proportions of child vocalizations that were speech-related as the children got older, $\beta = 0.535$, $p < .001$ (see *Statistics* Supplemental Material). The *Sound Types* Supplemental Material gives frequencies of other speaker labels and child vocalization types.

Testing the feedback loop hypothesis—Figure 2 helps illustrate how we tested to see whether the social feedback loop for speech development hypothesis was supported by the microstructure of vocal interactions. For a given recording we first tested whether a child vocalization containing speech-related material predicted whether or not that child vocalization received a response. We then tested whether a child's vocalization being speech-related or not could be predicted based on whether the child's most recent speech-related vocalization received a response.

A response was operationally defined as any adult vocal behavior occurring within 1 s after the child vocalization. This window was chosen to be the same as that used by Keller, Lohaus, Völker, Cappenberg, & Chasiotis (1999), motivated by the finding that a 1 s window is short enough for even young infants to detect temporal contingencies.

Contingency of adult responses on content of child vocalizations—Within a recording, contingency of adult response on child vocalization type was measured by taking the following difference:

$$\frac{n_{r,sp}}{n_{c,sp}} - \frac{n_{r,nonsp}}{n_{c,nonsp}}$$

where $n_{r,sp}$ is the number of adult responses to child speech-related vocalizations, $n_{c,sp}$ the number of child speech-related vocalizations, $n_{r,nonsp}$ the number of adult responses to child non-speech-related vocalizations, and $n_{c,nonsp}$ the number of child non-speech-related vocalizations (see the Contingency Computation Supplemental Material). For TD recordings in the matched subsample, the difference was positive, 0.065, $p < .001$, indicating that when child vocalizations were speech-related, they were more likely to receive an adult response (Fig. 4, top).

Effect of contingent adult responses on subsequent child vocalizations— Contingency of child speech-related vocalization on previous adult response was measured by taking the following difference:

$$\frac{n_{c,sp,r,sp}}{n_{c,r,sp}} - \frac{n_{c,sp,nor,sp}}{n_{c,nor,sp}}$$

where $n_{c,sp,r,sp}$ is the number of child vocalizations that were speech-related when the previous child speech-related vocalization received an adult response, $n_{c,r,sp}$ the number of child vocalizations of any type when the previous child speech-related vocalization received an adult response, $n_{c,sp,nor,sp}$ the number of child vocalizations that were speech-related when the previous child speech-related vocalization received no adult response, and $n_{c,nor,sp}$ the number of child vocalizations of any type when the previous child speech-related vocalization received no adult response (see the *Contingency Computation* Supplemental Material). For TD recordings in the matched subsample, the mean difference was 0.036, which was statistically greater than zero, $p < .001$, indicating that child vocalizations were more likely to be speech-related when the previous child speech-related vocalization received an adult response than when it did not receive an adult response (Fig. 4, bottom).

Autism Spectrum Disorder group

Overall vocalization rate—The number of child vocalizations of any type (either speech-related or not speech-related) per 12 hour recording was smaller for the ASD group than the TD group, $\beta = -0.274$, $p < .001$.

Speech related vocalization rate—The proportion of child vocalizations that contained speech-related material was lower in ASD compared to TD, $\beta = -0.275$, $p < .001$ (Fig. 3). There was a statistically significant interaction between age and diagnosis, $\beta = -0.111$, $p = .009$ such that the age-related increase in speech-related vocalization proportion was slower in ASD than in TD—the two groups tended to diverge with time.

Interaction dynamics—A diagonal cross recurrence profile (DCRP; Dale, Warlaumont, & Richardson, 2011; see *Cross-recurrence* Supplemental Material) was used to characterize the temporal relationship between all possible pairings (within a 10 s sliding window) of vocalizations from the child and vocalizations from the adult in order to compare generally the difference in quantity of interaction and leading-following relationships across groups. Average DCRPs for the TD and ASD groups are shown in Figure 5. The left side of the plot indicates pairings where the adult led the child; the right shows pairings where the child led the adult. Moving from the center of the plot outward represents increasing lag between child and adult.

The total area under the DCRP curve between lag -10 and lag 10, which we will call the DCRP height, measures the quantity of child-caregiver interaction. DCRP height was higher for the TD group than the ASD group, β = -.166, *p* = .001. The ratio of the right side (lag 0 to lag 10) height to the left side (lag -10 to lag 0) height indicates how much the child initiated vs. followed. This ratio was lower in ASD than in TD, β = −0.266, $p < .001$. These results corroborate previous findings of vocal interaction dynamics differences in autism, there being less interaction overall as well as a lower ratio of leading to following compared to TD children.

Contingency of adult responses on content of child vocalizations—As with the TD children, adult responses to vocalizations produced by the children with autism were more likely when the child vocalizations were speech-related: in the matched subsample ASD recordings, the difference between the proportion of speech-related child vocalizations receiving responses and the proportion of non-speech-related child vocalizations receiving responses averaged 0.048, $p < .001$. Although this contingency was present for both groups, it was weaker in ASD than in TD, β = −0.134, *p* = .008. Note that because our measure of response contingency normalizes for the number of child behaviors produced, the difference between ASD and TD is not a simple artifact of differences in number of child vocalizations across groups.

Effect of contingent adult responses on subsequent child vocalizations—As in TD, ASD child vocalization type was contingent on previous adult response: within the matched subsample ASD recordings the probability of a child vocalization being speech-related was on average 0.042 greater when the previous child speech-related vocalization received a response than when it did not receive a response, $p < .001$. There was no statistically significant difference between TD and ASD in the strength of this contingency.

Matched subsample results—All statistically significant differences between the ASD and TD groups were also statistically significant when analyzing only the gender-, age-, and SES-matched subsample except for the interaction between age and ASD status with respect to proportion of child vocalizations that were speech-related. This may be due to a reduction in statistical power, since previously published work (e.g., Oller et al., 2010) points to similar trends for divergence of TD and ASD vocalization types.

Age, maternal education, and gender

Here we list the statistically significant ($p < .05$) associations between age, maternal education, and gender and the various vocalization, interaction, and contingency measures.

The number of child vocalizations per day increased with age, β = 0.317, $p < .001$, and with maternal education, β = 0.220, $p < .001$. The proportion of child vocalizations that were speech-related increased with age, β = 0.467, $p < .001$, and with maternal education, β = 0.250, $p < .001$, and, as stated above, there was a significant increase with age and a significant interaction between age and ASD.

The DCRP was higher, indicating more child-caregiver interaction, as age increased, β = 0.185, $p < .001$, and as maternal education increased, β = 0.268, $p < .001$. There was an interaction between age and ASD status such that the growth in height of the DCRP was greater for the ASD group, β = 0.159, $p < .001$. There was a significant positive effect of maternal education on the ratio of the child to adult leading, $\beta = 0.166$, $p < .001$, and a significant negative interaction between age and autism such that the increase of the child leading ratio across age was slower in ASD, $\beta = -0.101$, $p = .022$.

The contingency of adult response on child vocalization being speech-related increased with age, $\beta = 0.111$, $p = .009$, and with maternal education, $\beta = 0.209$, $p < .001$. There were no statistically significant relationships between any demographic variables and the contingency of child vocalization type on whether the previous child speech-related vocalization received a response.

There were no statistically significant effects of gender on any of the dependent variables.

Simulation results

The differences in adult responding on child vocalization type and of child vocalization type on previous adult response were small in magnitude: both were on the order of .05. However, small contingencies can add up over many interactions over the course of the first few years of life to yield larger differences in child behavior. To demonstrate this quantitatively, we developed a simple computational model of the process (see *Computational Model* Supplemental Material). The model supports our contention that the observed differences in child vocalization rate and in contingency of adult response on child vocalization type underlie the divergence between ASD and TD groups in speech-related vocalization rate.

Discussion

We found that in typical development adult responding was contingent on the speech-relatedness of a child vocalization: speech-relatedness increased the likelihood of adult response. If adult responding were not sensitive to child vocal behavior, then we would not expect an above-chance increase in response probability for speech-related compared to non-speech-related child vocalizations. We also found that the likelihood of there being speech-related material within a child vocalization increased if the child's previous speech-related vocalization received an adult response. If it were the case that parents' responses were highly dependent on child behavior but that children did not learn from this information, we would expect not to find child vocalization type to be related to whether the previous child speech-related vocalization received a response. Together, our findings from microscopic analysis of naturalistic vocal interaction data support the idea that there is a social feedback loop between child and adult that facilitates speech development. Considering the huge number of child vocalizations that are produced within a day (on average well over 2,000) and accumulate over months and years, mutual contingencies between child and adult are expected to compound, contributing substantially to speech development. The results support our feedback loop theory, and our interpretations are consistent with reports of reliable contingencies being important for other aspects of language learning (Ramscar, Yarlett, Dye, Denny, & Thorpe, 2010; Ramscar, Dye, & Klein, 2013).

It should be noted that the present study is correlational. Future experiments are needed to confirm the causal status of the proposed feedback loop. For example, parents could be trained (or directly instructed on a moment-by-moment basis so as) to alter their response contingencies. Any effects on the children's vocal productions could then be determined. Additionally, if child vocalization could be increased while keeping adult response contingencies constant (perhaps by increasing response rates for all vocalizations but leaving the difference in response rate for speech-related vs. not-speech-related vocalizations constant), this could provide an experimental test of the importance of number of vocal learning opportunities.

As expected, we found that children with ASD produced fewer vocalizations and that a smaller proportion of those vocalizations were speech-related. There were also differences in the temporal patterning of vocal interactions with adults, as indicated by cross-recurrence analysis. The social feedback loop we found support for in typical development also appears to be operational in autism, as evidenced by the statistically significant contingency of adult response on child vocalization type and of child vocalization type on previous adult response. This is consistent with previous reports that child-caregiver interactions play an important role in development for children with ASD (Siller & Sigman, 2008; see also Anderson et al., 2007).

However, the feedback loop appears diminished in ASD in two ways. First, children with autism produce fewer vocalizations, perhaps due to endogenous differences in motor skills (Amorosa, 1992), differences in action selection (perhaps related to premature prefrontal cortex development; Courchesne & Pierce, 2005), or intrinsic motivation to communicate (Mundy & Crowson, 1997). A reduction in vocalization rate leads to fewer iterations of the social feedback loop, reducing the number of child opportunities to learn from contingent social feedback (see also Yoder, 1999; Tamis-LeMonda et al., 2001; and Leezenbaum et al., 2013).

Second, responses of adults interacting with children with autism are less contingent on the child vocalization being speech-related. This difference could be due to a variety of factors, such as increased attentional demands of parenting a child with special needs, genetic differences between parents of children with ASD and parents of TD children (Landa et al., 1992), or adults' learned expectations of the children's behavior (Yoder, 1999). A difference in adult's learned expectations would be consistent with there being a similar social feedback loop shaping adults' behaviors. Although outside the scope of the present study, it should be possible to test this by looking at analogous contingencies, i.e., the contingency of child responses on adult responses and the contingency of future adult responses on previous child responses to adult responses. Lastly, the reduced contingency of adult responses in the ASD group could also be due to lower quality of the speech-related vocalizations. In this study we considered only whether or not a child vocalization contained speech-related material, but the voice quality, the words and phrases it contains, its prosody, etc. likely also play a large role in determining the likelihood of adult response. Regardless of the reason, the reduction in adults' contingent responding again provides children with reduced opportunities to learn about the social effects of their vocal behavior.

Successful interventions targeting adult responding (Yoder & Stone, 2006; National Research Council, 2001) can be interpreted as affecting the feedback loop proposed here. For example, some interventions explicitly train parents to attend to their children's communicative attempts, including babbling and speech. Parents are asked to respond positively to these attempts, such as by providing encouraging comments and verbal expansions. Increased contingency of parent response on child vocalization speech-relatedness is a likely result. Even if parents increase their responsiveness indiscriminately to all types of infant vocalizations, including crying, fussing, babbling, singing, and speech, this can be expected to increase child overall vocalization rates, thereby increase the number of social feedback loop iterations, or learning opportunities, the child experiences. In some cases, parent-focused intervention appears to attenuate child communication growth (Carter, Messinger, Stone, Celimli, Nahmias, & Yoder, 2011); this could be the result of disrupting parents' natural contingent responding to child vocalizations. In the future, the effects of parent training on overall parent response rate, overall child vocalization rate, adult response contingency, and subsequent child vocalizations of different types, could be studied by sending audio recorders home with families undergoing such interventions and performing analyses like those performed here.

Third, the social feedback loop could be diminished if children with autism have reduced ability to attend to and make use of contingent social responses (Klin, 1991; Mundy & Crowson, 1997; Karmiloff-Smith, 1998; Mundy & Neal, 2001; Dawson et al., 2004). Such differences could ultimately stem from overgrowth in prefrontal and other cortical brain regions in children with ASD during the first year of life (Hazlett et al., 2011; Courchesne et al, 2011), which might be expected to affect learning from environmental contingencies (Thompson-Schill et al., 2009). Here we did not find any statistically significant differences in this contingency, which may reflect a true lack of difference across groups or merely a lack of sensitivity of the measure.

In addition to differences in ASD, we also observed differences with age and maternal education. Proportional frequency of speech-related vocalization, overall levels of interaction, and contingency of adult response on child vocalization type all increased with both age and maternal education. Higher maternal education was also associated with a higher ratio of child leading to adult leading. These results suggest that SES may also have substantial effects on the functioning of the social feedback loop, and they corroborate and extend previous reports of differences in child and parent behavior across SES (Hart & Risley, 1995; Hoff, 2003; Greenwood et al., 2010).

In summary, we propose a social feedback loop that supports speech development, wherein adults respond contingently to speech-related child vocalizations and children's vocalization characteristics are in turn contingent on previous adult responses. We explicitly tested each component of this social feedback loop using automated labeling and analysis of the microstructure of vocal interaction in daylong naturalistic recordings. The results support the role of the social feedback loop for speech development in children both with and without ASD. The results also revealed two ways in which ASD appears to reduce the effectiveness of the social feedback loop: (1) the disorder reduces the child vocal material that is available for adults to respond to and (2) the disorder is associated with decreases in adult response contingency on the child's behavior. Given the constructivist nature of the social feedback loop, these differences are expected to have accumulating, cascading effects across development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by a DOE CSGF (DE-FG02-97ER25308), the NIDCD (R01 DC011027), the Plough Foundation, and the LENA Research Foundation. We would also like to thank Dongxin Xu, Kim Coulter, Sharmi Gray, Rick Dale, Eugene Buder, Robert Kozma, Gert Westermann, Terrence Paul, the LENA Research Foundation, the participants, and the reviewers of this paper.

References

American Psychiatric Association. Diagnostic and statistical manual of mental disorders. Washington, DC: American Psychiatric Association; 2000.

Amorosa, H. Disorders of vocal signaling in children. In: Papušek, H.; Jürgens, U.; Papoušek, M., editors. Nonverbal vocal communication: Comparative and developmental approaches. Cambridge, UK: Cambridge University Press; 1992. p. 192-204.

Anderson DK, Lord C, Risi S, DiLavore PS, Shulman C, Thurm A, et al. Pickles A. Patterns of growth in verbal abilities among children with autism spectrum disorder. Journal of Consulting and Clinical Psychology. 2007; 75(4):594–604.10.1037/0022-006X.75.4.594 [PubMed: 17663613]

Bloom K. Quality of adult vocalizations affects the quality of infant vocalizations. Journal of Child Language. 1988; 15(3):469–480.10.1017/S0305000900012502 [PubMed: 3198716]

Carter AS, Messinger DS, Stone WL, Celimli S, Nahmias AS, Yoder P. A randomized controlled trial of Hanen's 'More Than Words' in toddlers with early autism symptoms. Journal of Child Psychology and Psychiatry. 2011; 52:741–752.10.1111/j.1469-7610.2011.02395.x [PubMed: 21418212]

Courchesne E, Pierce K. Brain overgrowth in autism during a critical time in development: Implications for frontal pyramidal neuron and interneuron development and connectivity. International Journal of Developmental Neuroscience. 2005; 23:153–170.10.1016/j.ijdevneu.2005.01.003 [PubMed: 15749242]

Courchesne E, Mouton PR, Calhoun ME, Semendeferi K, Ahrens-Barbeau C, Hallet MJ, et al. Pierce K. Neuron number and size in prefrontal cortex of children with autism. Journal of the American Medical Association. 2011; 306(18):2001–2010.10.1001/jama.2011.1638 [PubMed: 22068992]

Dale R, Warlaumont AS, Richardson DC. Nominal cross recurrence as a generalized lag sequential analysis for behavioral streams. International Journal of Bifurcation and Chaos. 2011; 21(4):1153–1161.10.1142/S0218127411028970

Dawson G, Toth K, Abbott R, Osterling J, Munson J, Estes A, Liaw J. Early social attention impairments in autism: Social orienting, joint attention, and attention to distress. Developmental Psychology. 2004; 75(2):271–283.10.1037/0012-1649.40.2.271 [PubMed: 14979766]

Girolametto LE. Improving the social-conversational skills of developmentally delayed children: An intervention study. Journal of Speech and Hearing Disorders. 1988; 53(2):156–167. [PubMed: 2452300]

Goldstein MH, King AP, West MJ. Social interaction shapes babbling: Testing parallels between birdsong and speech. Proceedings of the National Academy of Sciences of the United States of America. 2003; 100(13):8030–8035.10.1073/pnas.1332441100 [PubMed: 12808137]

Goldstein MH, Schwade JA. Social feedback to infants' babbling facilitates rapid phonological learning. Psychological Science. 2008; 19(5):515–523.10.1111/j.1467-9280.2008.02117.x [PubMed: 18466414]

Greenwood CR, Thiemann-Bourque K, Walker D, Buzhardt J, Gilkerson J. Assessing children's home language environments using automatic speech recognition technology. Communication Disorders Quarterly. 2010; 32(2):83–92.10.1177/1525740110367826

Hart, B.; Risley, TR. Meaningful differences in the everyday experience of young American children. Baltimore, MD: Paul H. Brookes Publishing Co; 1995.

Hazlett HC, Poe MD, Gerig G, Styner M, Chappell C, Smith RG, et al. Piven J. Early brain overgrowth in autism associated with increase in cortical surface area before age 2 years. Archives of General Psychiatry. 2011; 68(5):467–476.10.1001/archgenpsychiatry.2011.39 [PubMed: 21536976]

Hoff E. The specificity of environmental influence: Socioeconomic status affects early vocabulary development via maternal speech. Child Development. 2003; 74(5):1368–1378.10.1111/1467-8624.00612 [PubMed: 14552403]

Jaffe J, Beebe B, Feldstein S, Crown CL, Jasnow MD. Rhythms of dialogue in infancy: Coordinated timing in development. Monographs of the Society for Research in Child Development. 2001; 66(2):vii–viii. 1–132.

Karmiloff-Smith A. Development itself is the key to understanding developmental disorders. Trends in Cognitive Sciences. 1988; 2(10):389–398.10.1016/S1364-6613(98)01230-3 [PubMed: 21227254]

Keller H, Lohaus AV, Völker S, Cappenberg M, Chasiotis A. Temporal contingency as an independent component of parenting behavior. Child Development. 1999; 70(2):474–485.10.2307/1132101

Klin A. Young autistic children's listening preferences in regard to speech: A possible characterization of the symptom of social withdrawal. Journal of Autism and Developmental Disorders. 1991; 21(1):29–42.10.1007/BF02206995 [PubMed: 1828067]

Landa R, Piven J, Wzorek MM, Gayle JO, Chase GA, Folstein SE. Social language use in parents of autistic individuals. Psychological Medicine. 1992; 22(1):245–254.10.1017/S0033291700032918 [PubMed: 1574562]

Leezenbaum NB, Campbell SB, Butler D, Iverson JM. Maternal verbal responses to communication of infants at low and heightened risk of autism. Autism. 201310.1177/1362361313491327

Mundy P, Crowson M. Joint attention and early social communication: Implications for research on intervention with autism. Journal of Autism and Developmental Disorders. 1997; 27(6):653–676.10.1023/A:1025802832021 [PubMed: 9455727]

Mundy, P.; Neal, AR. Neural plasticity, joint attention, and a transactional social-orienting model of autism. In: Glidden, LM., editor. International Review of Research in Mental Retardation: Autism. San Diego, CA: Academic Press; 2000. p. 139-168.

Lord, C.; McGee, JP., editors. National Research Council. Educating Children with Autism. Washington, DC: National Academy Press; 2001.

Oller, DK. The emergence of the speech capacity. Mahwah, NJ: Lawrence Erlbaum Associates; 2000.

Oller DK, Niyogi P, Gray S, Richards JA, Gilkerson J, Xu D, et al. Warren SF. Automated vocal analysis of naturalistic recordings from children with autism, language delay, and typical development. Proceedings of the National Academy of Sciences of the United States of America. 2010; 107(30):13354–13359.10.1073/pnas.1003882107 [PubMed: 20643944]

Patten E, Belardi K, Baranek GT, Watson LR, Labban JD, Oller DK. Vocal patterns in infants with autism spectrum disorder: Canonical babbling status and vocalization frequency. Journal of Autism and Developmental Disorders. 2014 doi: 0.1007/s10803-014-2047-4.

Paul R, Fuers Y, Ramsay G, Chawarska K, Klin A. Out of the mouth of babes: Vocal production in infant siblings of children with ASD. Journal of Child Psychology and Psychiatry. 2011; 52(5): 588–598.10.1111/j.1469-7610.2010.02332.x [PubMed: 21039489]

Paul R, Orlovski SM, Marcinko HC, Volkmar F. Conversational behaviors in youth with high-functioning ASD and Asperger syndrome. Journal of Autism and Developmental Disorders. 2009; 39(1):115–125.10.1007/s10803-008-0607-1 [PubMed: 18607708]

Peppé S, McCann J, Gibbon F, O'Hare A, Rutherford M. Receptive and expressive prosodic ability in children with high-functioning autism. Journal of Speech, Language, and Hearing Research. 2007; 50(4):1015–1028.10.1044/1092-4388(2007/071)

Ramscar M, Dye M, Klein J. Children value informativity over logic in word learning. Psychological Science. 2013; 24(6):1017–1023.10.1177/0956797612460691 [PubMed: 23610135]

Ramscar M, Yarlett D, Dye M, Denny K, Thorpe K. The effects of feature-label-order and their implications for symbolic learning. Cognitive Science. 2010; 34(6):909–957.10.1111/j. 1551-6709.2009.01092.x [PubMed: 21564239]

Sheinkopf SJ, Iverson JM, Rinaldi ML, Lester BM. Atypical cry acoustics in 6-month-old infants at risk for autism spectrum disorder. Autism Research. 2012; 5(5):331–339.10.1002/aur.1244 [PubMed: 22890558]

Sheinkopf SJ, Mundy P, Oller DK, Steffens M. Vocal atypicalities of preverbal autistic children. Journal of Autism and Developmental Disorders. 2000; 30(4):245–354.10.1023/A:1005531501155 [PubMed: 11055460]

Siller M, Sigman M. Modeling longitudinal change in the language abilities of children with autism: Parent behaviors and child characteristics as predictors of change. Developmental Psychology. 2008; 44(6):1691–1704.10.1037/a0013771 [PubMed: 18999331]

Tamis-LeMonda CS, Bornstein MH, Baumwell L. Maternal responsiveness and children's achievement of language milestones. Child Development. 2001; 72(3):748–767.10.1111/1467-8624.00313 [PubMed: 11405580]

Thompson-Schill S, Ramscar M, Chrysikou E. Cognition without control: When a little frontal lobe goes a long way. Current Directions in Psychological Science. 2009; 8(5):259–263. [PubMed: 20401341]

Warren S, Gilkerson J, Richards J, Oller DK, Xu D, Yapanel U, Gray S. What automated vocal analysis reveals about the language learning environment of young children with autism. Journal of Autism and Developmental Disorders. 2010; 40(5):555–569.10.1007/s10803-009-0902-5 [PubMed: 19936907]

Yoder PJ. Maternal responsivity mediates the relationship between prelinguistic intentional communication and later language. Journal of Early Intervention. 1999; 22(2):126–136.10.1177/105381519902200205

Yoder PJ, Stone WL. A randomized comparison of the effect of two prelinguistic communication interventions on the acquisition of spoken communication in preschoolers with ASD. Journal of Speech, Language, and Hearing Research. 2006; 49(4):698–711.10.1044/1092-4388(2006/051)

Zwaigenbaum L, Bryson S, Rogers T, Roberts W, Brian J, Szatmari P. Behavioral manifestations of autism in the first year of life. International Journal of Developmental Neuroscience. 2005; 23(2–3):1430–152. doi: http://dx.doi.org/10.1016/j.ijdevneu.2004.05.001.

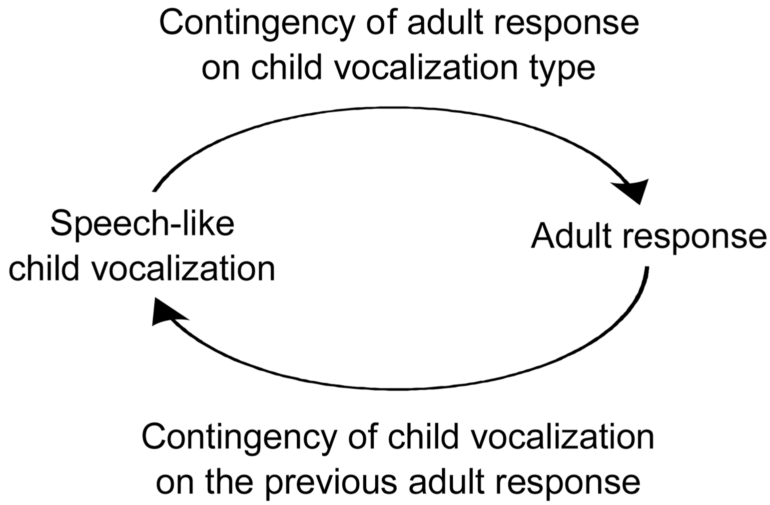

Figure 1.
The proposed social feedback loop.

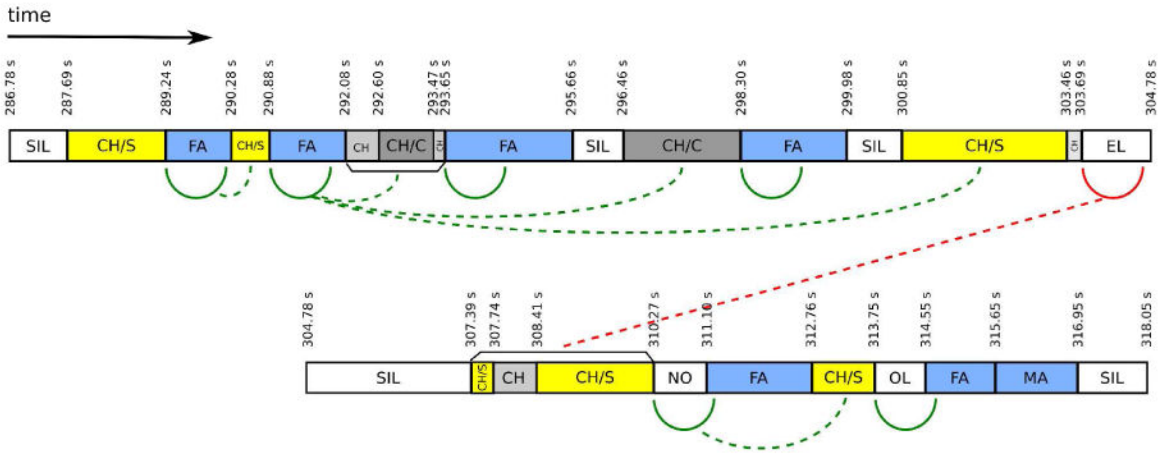

Figure 2.

Example, from a subsection of one recording, of sound source labels and how adult responses and child dependence on adult responses were measured. Yellow (CH/S): child speech-related vocalizations; dark gray (CH/C): child cry/vegetative vocalizations; light gray (CH): unspecified child vocalization segments; blue (FA and MA): female adult and male adult vocalization segments; white (SIL, EL, NO, and OL): silence, electronic sounds, noise, and overlap. Solid green curves: adult vocalization followed within one second after the end of a child vocalization and was thus considered a response. Solid red curve: child did not receive an adult response within the one-second window after the end of the child vocalization. Dashed green curves: child vocalization where the previous speech-related vocalization received an adult response. Dashed red line: a child vocalization where the previous child speech-related vocalization did not receive an adult response.

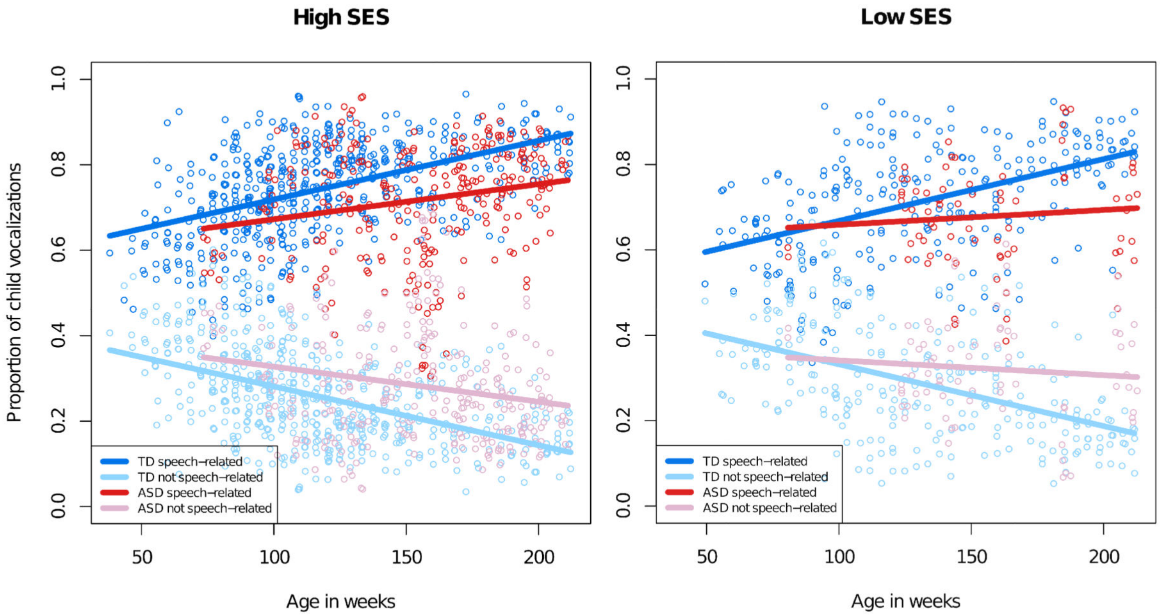

Figure 3.

Proportions of child vocalizations that were speech-related and not speech-related. Each point represents one 12-hour recording. Straight lines are linear regressions.

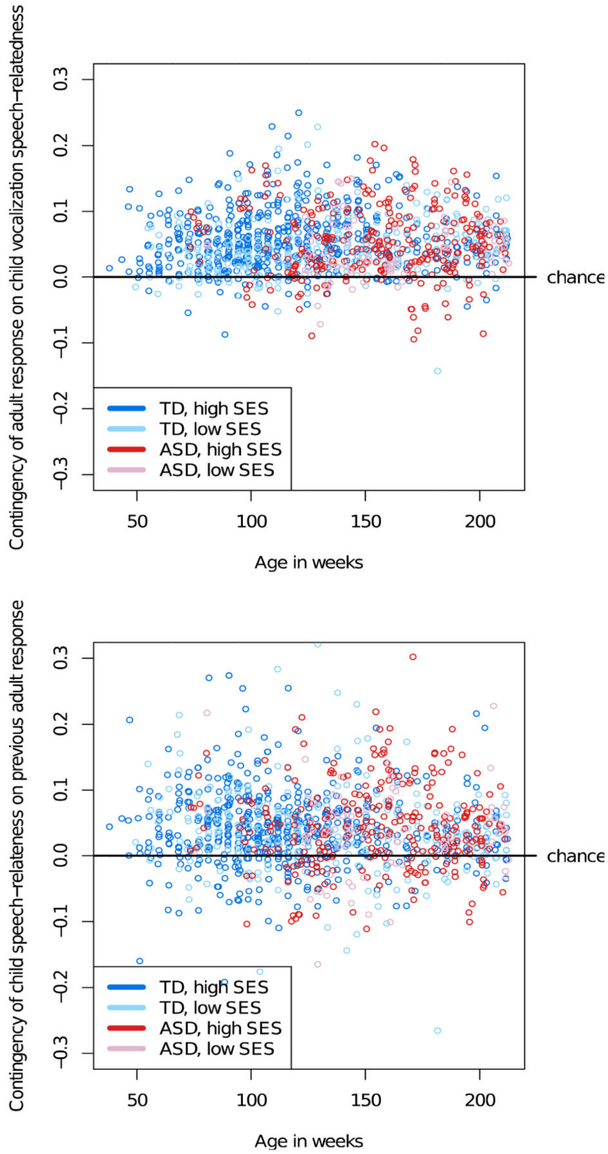

Figure 4.

Top: For each recording, the proportion of speech-related vocalizations receiving an immediate adult response minus the proportion of non-speech-related vocalizations receiving an adult response. Bottom: For each recording, the proportion of child vocalizations that were speech-related when the previous speech-related vocalization had received an adult response minus the proportion of child vocalizations that were speech-related when the previous speech-related vocalization had not received an adult response.

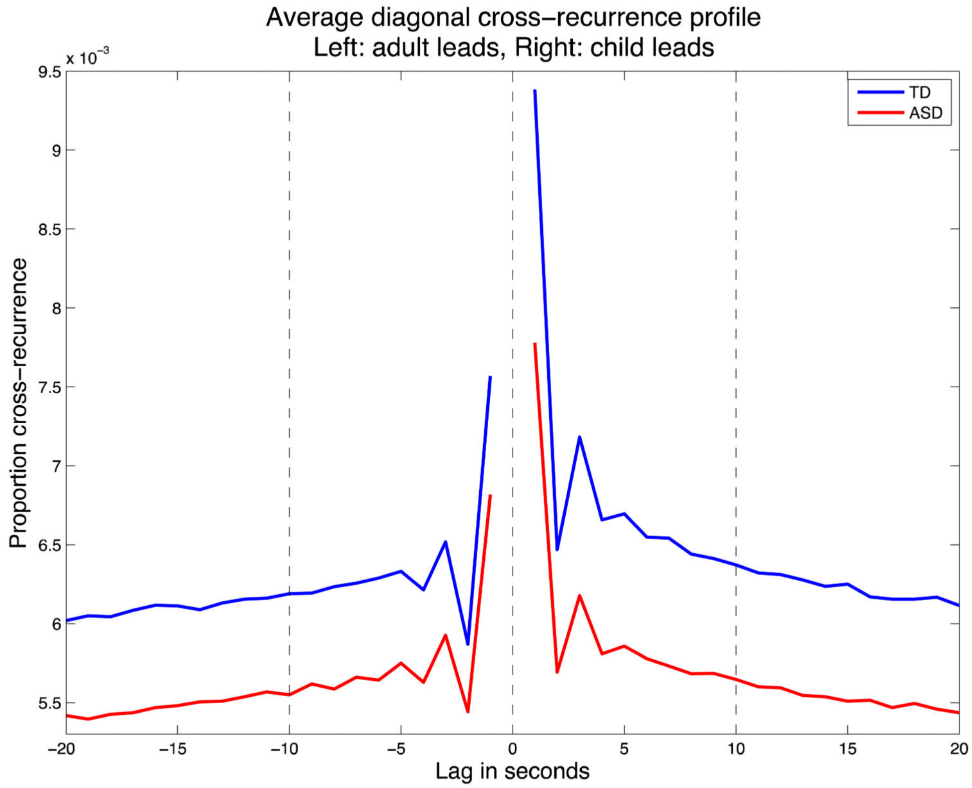

Figure 5.

Diagonal cross recurrence profile (DCRP), averaged across all TD recordings and all ASD recordings within the matched subsample.