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Psychological Science published online 19 May 2014
DOI: 10.1177/0956797614531023

The online version of this article can be found at:
http://pss.sagepub.com/content/early/2014/05/12/0956797614531023

Published by:
SAGE
http://www.sagepublications.com

On behalf of:
Association for Psychological Science

Psychological Science OnlineFirst, published on May 19, 2014 as doi:10.1177/0956797614531023

Research Article

Psychological Science
1–11

DOI: 10.1177/0956797614531023
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A Social Feedback Loop for Speech Development and Its Reduction in Autism

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Abstract

We analyzed the microstructure of child-adult interaction during naturalistic, daylong, automatically labeled audio recordings (13,836 hr total) of children (8- to 48-month-olds) with and without autism. We found that an adult was more likely to respond when the child's vocalization was speech related rather than not speech related. In turn, a child's vocalization was more likely to be speech related if the child's previous speech-related vocalization had received an immediate adult response rather than no response. Taken together, these results are consistent with the idea that there is a social feedback loop between child and caregiver that promotes speech development. Although this feedback loop applies in both typical development and autism, children with autism produced proportionally fewer speech-related vocalizations, and the responses they received were less contingent on whether their vocalizations were speech related. We argue that such differences will diminish the strength of the social feedback loop and have cascading effects on speech development over time. Differences related to socioeconomic status are also reported.

Keywords

social interaction, speech development, autism, socioeconomic status, rewards

Received 3/12/13; Revision accepted 2/20/14

Learning to produce vocalizations with speechlike acoustics is an essential component of early spoken-language learning (Oller, 2000). Here, we propose a positive social feedback loop supporting speech development (Fig. 1). When a child produces a sound, the child is more likely to receive an immediate, positive response from an adult if the sound contains speech or speech-related material than if it does 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. This proposal is in keeping with constructivist theories of cognitive development (Karmiloff-Smith, 1998; Leezenbaum, Campbell, Butler, & Iverson, 2013): Children's behaviors affect environmental input, and atypicalities are expected to have cascading effects on later speech ability.

The existence of this social feedback loop is supported by experiments showing that infants tend to produce more frequent speech-related (i.e., noncry, nonlaugh, and nonvegetative) vocalizations if their caregivers' responses are contingent on the infants' vocalizations than if their caregivers' responses are not contingent on the infants' 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 similarity to speech, more vowel resonance, or better consonant-vowel timing (Bloom, 1988; Goldstein & Schwade,

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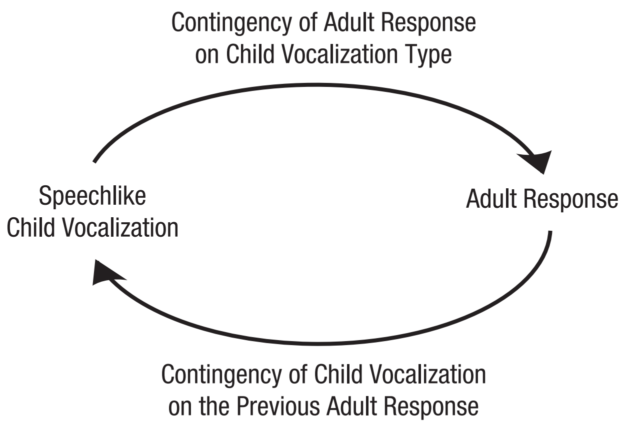

Fig. 1. The proposed social feedback loop. An adult is more likely to respond to a child's vocalization if the sound contains speech or speech-related material than if it does not contain speech or speech-related material (contingency of adult response). In turn, receiving an immediate response encourages the child to produce similar utterances (contingency of child vocalization).

2008). Additionally, a mother's responsiveness to her child's communicative behaviors predicts the child's language performance at a later age in the case of both typically developing (TD) infants (e.g., Tamis-LeMonda, Bornstein, & Baumwell, 2001) and children with developmental disabilities (Girolametto, 1988; Yoder, 1999), and greater vocal coordination between infant and adult predicts better language, cognitive, and perceptual ability at a later time (Greenwood, Thiemann-Bourque, Walker, Buzhardt, & Gilkerson, 2010; Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001). Note that the learning mechanisms that utilize these contingencies need not be explicit (Thompson-Schill, Ramscar, & Chrysikou, 2009).

Research on this social feedback loop could potentially improve 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, compared with typical development, ASD is associated with less social interaction, less frequent initiation of social interactions, and atypical turn-taking patterns (American Psychiatric Association, 2000; Anderson et al., 2007; Dawson et al., 2004; Paul, Orlovski, Marcinko, & Volkmar, 2009; Sheinkopf, Mundy, Oller, & Steffens, 2000; Warren et al., 2010; Zwaigenbaum et al., 2005). Children with or at high risk for ASD also tend to produce fewer speech-related vocalizations (Patten et al., 2014; Paul, Fuers, Ramsay, Chawarska, & Klin, 2011; Warren et al., 2010), and their vocalizations tend to be atypical (Oller et al., 2010; Patten et al., 2014; Paul et al., 2011; Paul et al., 2009; Peppé, McCann, Gibbon, O'Hare, & Rutherford, 2007; Sheinkopf, Iverson, Rinaldi, & Lester, 2012; Sheinkopf et al., 2000). Children with ASD also typically acquire language relatively slowly (Anderson et al., 2007).

Considering this proposed feedback loop may further 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 or fewer vocalizations that are speech related, compared with TD children. Second, caregivers of children with ASD might respond differently to their children's vocalizations. Third, children with ASD might differ from TD children in their ability to learn from adults' contingent responses.

In the study reported here, we utilized daylong naturalistic recordings and automated labeling and analysis to look for evidence of the proposed feedback loop in moment-to-moment interactions. We first analyzed data from TD children to determine (a) whether children's speech-related vocalizations are more likely than their non-speech-related vocalizations to receive immediate responses from adults and (b) whether a child's vocalization is more likely to be speech related if the child's previous speech-related vocalization received an immediate response. Next, we compared the frequencies of children's vocalizations and the patterns of child-caregiver vocal interaction for TD versus ASD children. We then tested whether the contingency of adults' responses and the contingency of children's vocalizations predicted by the feedback-loop hypothesis hold for children with ASD and whether these two contingencies differ between ASD and TD children.

We also tested for possible effects of children's age, maternal education level, and children's gender. We expected that as maternal education increased, children's rate of speech-related vocalization and child-adult interactivity would increase; we expected both of these measures to increase with children's age as well (Greenwood et al., 2010; Hart & Risley, 1995). We also tested whether the two contingencies of the social feedback loop differ across levels of maternal education or across age.

Method

Our data came from a subset of the recordings used in a previous study (Oller et al., 2010). The TD participants were 106 children (45% male, 55% female) 8 to 48 months of age. The ASD participants were 77 children (83% male, 17% female) 16 to 48 months of age; all children in this group had been diagnosed with the autism subtype of ASD, except for those who were too young for an autism diagnosis and so were categorized under pervasive developmental disorder not otherwise specified. Seventy-six participants in the TD group were recruited from the Denver, Colorado, area. The other TD participants and all the ASD participants were recruited from across the United States. Maternal education level, which we used as a proxy for socioeconomic status (SES), ranged widely in both groups, from some high school education to a

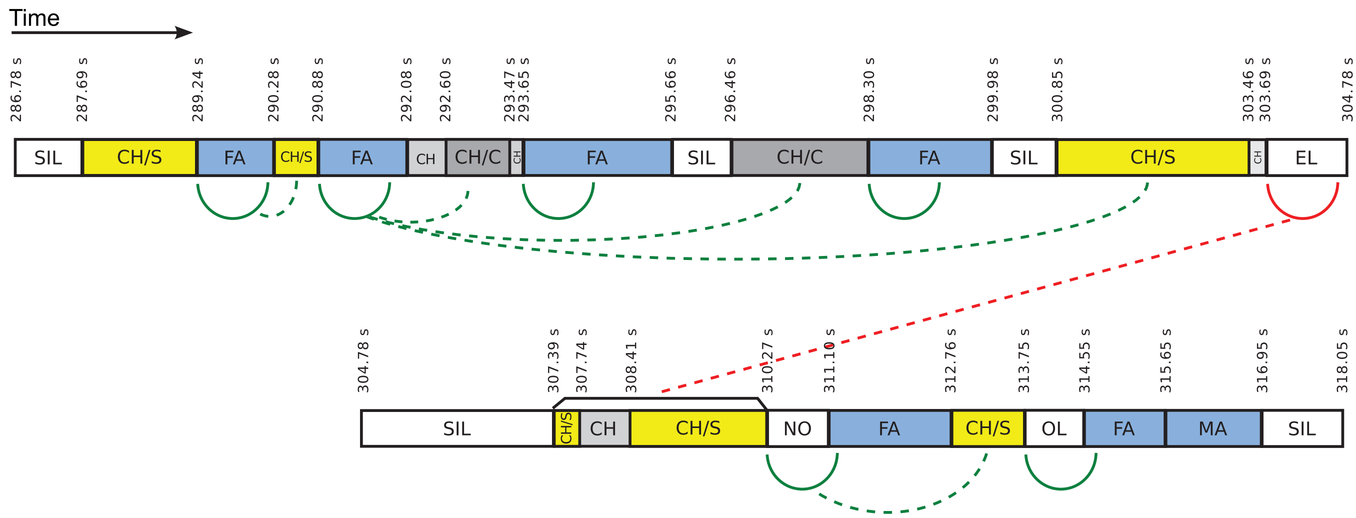

Fig. 2. Example (from a subsection of one recording) of sound-source labels and how adult responses and child dependence on adult responses were measured. Segments are color-coded as follows: Yellow ("CH/S") corresponds to the child's speech-related vocalizations; dark gray ("CH/C") to the child's non-speech-related vocalizations; light gray ("CH") to the child's unspecified vocalizations; blue ("FA" and "MA") to vocalizations of female and male adults, respectively; and white ("SIL," "EL," "NO," and "OL") to silence, electronic sounds, noise, and overlap, respectively. An adult vocalization that followed the end of the child's vocalization within 1 s was considered a response and is indicated by a solid green curve. The solid red curve marks the absence of an adult response to the child's vocalization within the 1-s window. The dashed curves indicate whether the child's vocalization followed a previous speech-related vocalization that received an adult response (green) or did not receive an adult response (red).

graduate degree. (More details on recruitment and characteristics of the two groups can be found in the Supporting Information of Oller et al., 2010.)

Recordings were made and preprocessed 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 hr; when recordings lasted longer than 12 hr, only the first 12 hr were analyzed. Recordings took place in varied settings, including the home, car, preschool, and, for the ASD group, speech-language therapy. In total, 1,153 recordings (13,836 hr) were included. The Essex Institutional Review Board approved the procedures.

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. For this study, we attended to only two types of sound sources: the child wearing the recorder and any adult (whether male or female). Within the segments of child vocalization, the system identified subsegments, labeling them as speech related (speech, nonword babble, and singing) or as non-speechlike (laughing, crying, burping, coughing, etc.). Segment Extraction in the Supplemental Material gives more information about how segment information was obtained and about reliability of the automatic labeling.

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 Data and Scripts in the Supplemental Material. (Questions about gaining access to the raw data or other database information beyond what is provided in the Supplemental Material should be directed to info@lenafoundation.org.)

For comparison with previous work, all analyses were also run on an alternative data set (Warren et al., 2010) that yielded results very similar to those reported here (see Alternative Data Set in the Supplemental Material). In addition, we created and analyzed a 426-recording subsample from the main data set that matched the ASD and TD groups on gender, age, and SES (see Matched Subsample in the Supplemental Material) to ensure that our primary findings were not affected by gender, age, or SES imbalance between the ASD and TD groups and to facilitate visualization and computational modeling. Except where otherwise noted, all patterns of statistical significance comparing across ASD and TD groups were the same for the matched subsample as for the main data set, and we focus here on the results for the main data set.

The methods used for testing statistical significance are described in Statistics in the Supplemental Material.

Results

TD group

Speech-related vocalization rate. Figure 3 shows the relative frequency of speech-related and non-speech-related vocalizations produced by the TD children as a

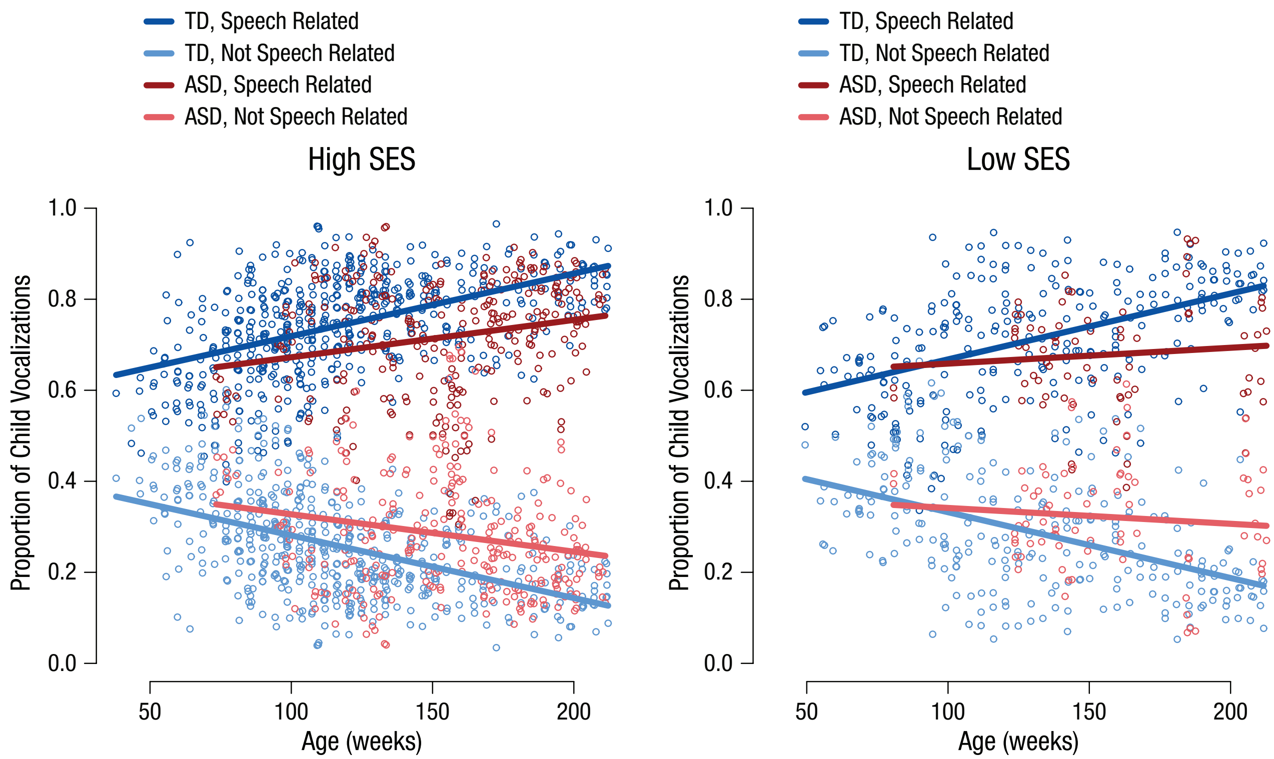

Fig. 3. Proportions of speech-related and non-speech-related vocalizations of the typically developing (TD) children and children with autism spectrum disorder (ASD) as a function of age. Results presented here are from the main data set. Each point represents one 12-hr recording. Straight lines are best-fitting linear regression lines. Results are presented separately for children from families of high and low socioeconomic status (SES). Family SES was defined by maternal level of education; a family was considered to have high SES if the mother had an associate degree or higher and to have low SES if the mother's level of education was below an associate degree.

function of age. (For visualization purposes, the figure shows the data separately for infants whose mothers had low and high levels of education, but in our statistical analyses, we used more specific maternal education levels, which could range from 1 to 7; see Warren et al., 2010.) The proportion of speech-related vocalizations increased with children's age, $\beta = 0.535$, $p < .001$. (For information about the quantities of other types of vocalizations in recordings of both groups and the relationship of these quantities to demographic variables, see Sound Types in the Supplemental Material.)

Testing the feedback-loop hypothesis. Figure 2 helps illustrate how we tested to see whether the microstructure of vocal interactions supported our hypothesis. For a given recording, we first tested whether the presence or absence of speech-related material in a child's vocalization predicted whether that vocalization received a response. We then tested whether the presence or absence of speech-related material in a child's vocalization could be predicted from whether the child's most recent speech-related vocalization had 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, and Chasiotis (1999), and was motivated by the finding that a 1-s window is short enough for even young infants to detect the temporal contingency.

Within a recording, contingency of adults' responses on the child's 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 the child's speech-related vocalizations, $n_{c,sp}$ is the number of the child's speech-related vocalizations, $n_{r,nonsp}$ is the number of adult responses to the child's non-speech-related vocalizations, and $n_{c,nonsp}$ is the number of the child's non-speech-related vocalizations (see Contingency Computation in the Supplemental Material). For TD recordings, this difference was positive, .052, $p < .001$ (the corresponding value for the matched subsample was .065). Thus, children's vocalizations were more likely to receive an adult response if they were speech related than if they were not (Fig. 4, left panel; note that Fig. 4,

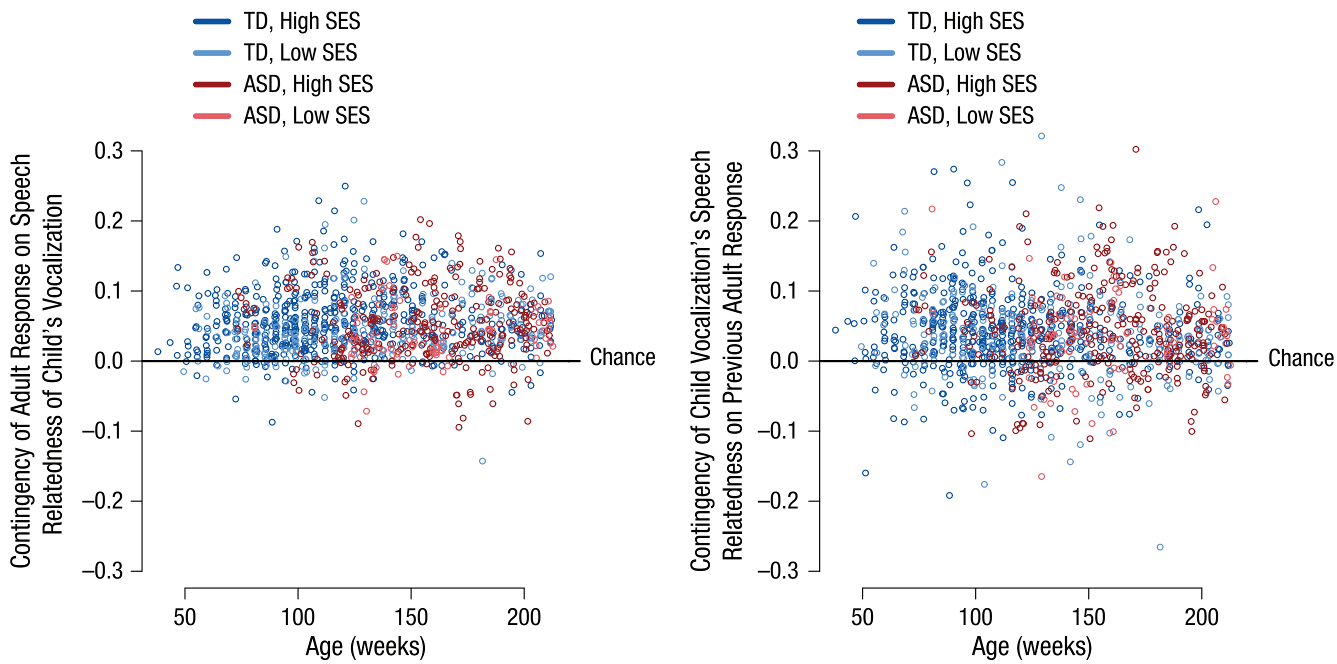

Fig. 4. Contingencies of adults' responses and children's vocalization types as a function of age. Results presented here are from the main data set. The left panel shows the difference between the proportion of children's speech-related vocalizations receiving an immediate adult response and the proportion of children's non-speech-related vocalizations receiving an adult response. The right panel shows the difference between the proportion of children's vocalizations that were speech related when the previous speech-related vocalization had received an adult response and the proportion of children's vocalizations that were speech related when the previous speech-related vocalization had not received an adult response. Each plotted point represents a single recording from either the typically developing (TD) or autism spectrum disorder (ASD) group; these groups were further subdivided by socioeconomic status (SES; see Fig. 3).

like Fig. 3, shows the data separately for infants whose mothers had low and high levels of education).

Contingency of children's 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 child's number of vocalizations that were speech related when the child's previous speech-related vocalization received an adult response, $n_{c,r,sp}$ is the child's number of vocalizations of any type when the child's previous speech-related vocalization received an adult response, $n_{c,sp,nor,sp}$ is the child's number of vocalizations that were speech related when the child's previous speech-related vocalization received no adult response, and $n_{c,nor,sp}$ is the child's number of vocalizations of any type when the child's previous speech-related vocalization received no adult response (see Contingency Computation in the Supplemental Material). For TD recordings, the mean difference was .039, which was statistically greater than zero, $p < .001$ (the corresponding value for the matched subsample was .036). Thus, a child's vocalization was more likely to be speech related when the child's previous speech-related vocalization had received an adult response than when it had not received an adult response (Fig. 4, right panel).

Comparison of the TD and ASD groups

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

Speech-related vocalization rate. The proportion of children's vocalizations that contained speech-related material was lower in the ASD group compared with the TD group, $\beta = -0.275$, $p < .001$ (Fig. 3). There was a statistically significant interaction between age and group, $\beta = -0.111$, $p = .009$; the age-related increase in the proportion of speech-related vocalizations was slower in the ASD group than in the TD group, such that the two groups tended to diverge with time. This interaction was not statistically significant within the matched subsample, perhaps because of a reduction in statistical power, as previously published work (e.g., Oller et al., 2010) has

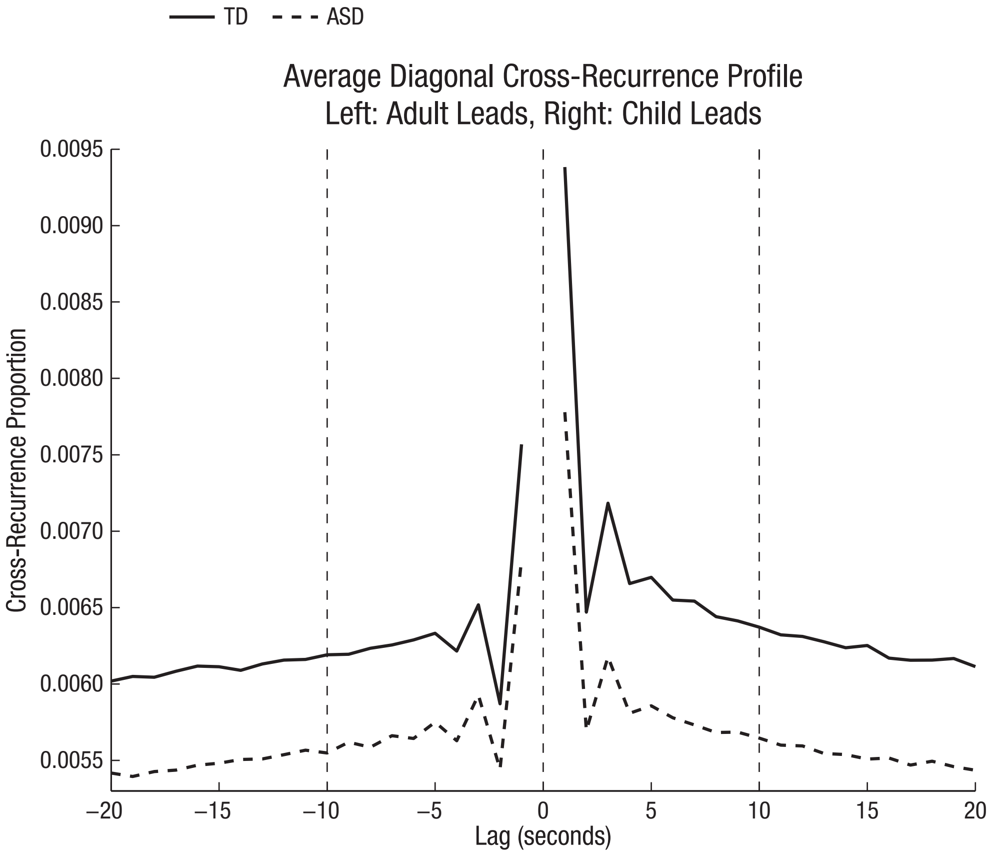

Fig. 5. Diagonal cross-recurrence profile (DCRP) averaged across all recordings of the typically developing (TD) and autism spectrum disorder (ASD) groups within the matched subsample.

also found age-related divergence between TD and ASD children in the frequency of different vocalization types.

Interaction dynamics. A diagonal cross-recurrence profile (DCRP; Dale, Warlaumont, & Richardson, 2011; see Cross-Recurrence in the Supplemental Material) was used to characterize the temporal relationship of all possible pairings (within a 10-s sliding window) between vocalizations from a child and the corresponding adult (or adults) in order to examine whether the TD and ASD groups differed in the overall quantity of interaction and in leading-following relationships. Figure 5 shows average DCRPs for the two groups in the matched subsample only, so that the means for the groups can be directly compared. The left side of the plot indicates pairings in which the adult's vocalization preceded the child's; the right shows pairings in which the child's vocalization preceded the adult's. Lag increases from the center of the plot outward.

The total area under the DCRP curve between lag −10 and lag 10, which we call the DCRP height, measures the quantity of child-caregiver interaction. DCRP height was greater for the TD group than for the ASD group, $\beta = -0.166$, $p = .001$. The ratio of the right side's height (lag 0 to lag 10) to the left side's height (lag −10 to lag 0) indicates how much the child initiated as opposed to followed. This ratio was lower in the ASD group than in the TD group, $\beta = -0.266$, $p < .001$. These results corroborate previous findings of a difference in vocal interaction dynamics, there being less interaction overall as well as a lower ratio of leading to following for children with autism compared with TD children.

Contingency of adults' responses on the content of children's vocalizations. As was the case with the TD children, adults were more likely to respond to vocalizations produced by the children with autism when those vocalizations were speech related (Fig. 4, left panel): In the ASD recordings of the main data set, the difference between the proportion of children's speech-related vocalizations receiving responses and the proportion of children's non-speech-related vocalizations receiving responses averaged .050, $p < .001$ (the corresponding value for the matched subsample was .048). Although this contingency was present for both groups, it was weaker in the ASD group than in the TD group,

$\beta = -0.134$, $p = .008$. Note that because our measure of response contingency was normalized for the number of vocalizations the child produced, the difference between the groups was not a simple artifact of differences in the children's volubility between the groups.

Contingency of the content of children's responses on adult responses. As for the TD group, the content of children's vocalizations in the ASD group was contingent on previous adult response (Fig. 4, right panel): Within the ASD recordings in the main data set (and also in the matched subsample), the probability of a child's vocalization being speech related was on average .042 (also .042 for the matched subsample) greater when the child's previous speech-related vocalization had received a response than when it had not received a response, $p < .001$. There was no statistically significant difference between the TD and ASD groups in the strength of this contingency.

Age, maternal education, and gender

In this section, we summarize the statistically significant ($p < .05$) associations of age, maternal education, and gender with the various vocalization, interaction, and contingency measures within the main data set.

Children's numbers of vocalizations per day increased with age, $\beta = 0.317$, $p < .001$, and with maternal education, $\beta = 0.220$, $p < .001$. The proportion of children's vocalizations that were speech related also increased with age, $\beta = 0.467$, $p < .001$, and with maternal education (Fig. 3), $\beta = 0.250$, $p < .001$, and, as stated earlier, there was a significant interaction between age and group.

The DCRPs were higher, indicating more child-caregiver interaction, as children's age increased, $\beta = 0.185$, $p < .001$, and as maternal education increased, $\beta = 0.268$, $p < .001$. There was an interaction between age and group such that the growth in height of the DCRP was greater for the ASD group than for the TD group, $\beta = 0.159$, $p < .001$. There was a significant positive effect of maternal education on the ratio of child leading to adult leading, $\beta = 0.166$, $p < .001$, and a significant negative interaction between children's age and group for this measure, $\beta = -0.101$, $p = .022$. Follow-up tests indicated that this interaction reflected the fact that there was a significant increase of the child-leading ratio with age in the TD group but no significant change in this ratio with age in the ASD group.

The contingency of adults' responses on the speech relatedness of children's vocalizations increased with children's age, $\beta = 0.111$, $p = .009$, and with maternal education (Fig. 4), $\beta = 0.208$, $p < .001$. There were no statistically significant relationships between age or maternal education and the contingency of children's vocalization type on whether their previous speech-related vocalization had received response (Fig. 4).

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

Simulation results

The contingency of adults' responses on children's vocalization type and the contingency of children's vocalization type on adults' previous response were small in magnitude: The means for the ASD and TD groups were all between .03 and .07. However, small contingencies can add up over many interactions over the course of the first few years of life to yield larger differences in a child's behavior. To demonstrate this quantitatively, we developed a simple computational model of the process (see Computational Model Description and Computational Model Code and Data in the Supplemental Material). The model supports our contention that the observed differences in children's vocalization rates and in contingency of adults' responses on children's vocalization type underlie the divergence between the ASD and TD groups in their speech-related vocalization rates.

Discussion

We found that in typical development, adult responding was contingent on the speech relatedness of a child's vocalization: Speech relatedness increased the likelihood of adult response. If adult responding were not sensitive to children's vocal behavior, then we should not have observed an above-chance increase in response probability for children's speech-related vocalizations compared with their non-speech-related vocalizations. We also found that the likelihood of there being speech-related material within a child's vocalization increased if the child's previous speech-related vocalization had received an adult response. If it were the case that parents' responses were highly dependent on their children's behavior but that children did not learn from this information, we should not have found children's vocalization type to be related to whether their previous speech-related vocalization had 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 vocalizations that a child produces within a day (on average, well over 2,000) and the accumulation of this number over months and years, mutual contingencies between child and adult should contribute substantially to speech development. The results support our feedback-loop hypothesis, and our interpretations are consistent with reports of reliable contingencies being important for other aspects of language learning

(Ramscar, Dye, & Klein, 2013; Ramscar, Yarlett, Dye, Denny, & Thorpe, 2010).

It should be noted that this study was 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) to alter their response contingencies, and any effects on the children's vocal productions could then be determined. Additionally, if children's vocalizations could be increased while keeping adults' 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 the number of vocal learning opportunities.

As expected, we found that children with ASD produced fewer vocalizations than TD children did and that a smaller proportion of their vocalizations were speech related. There were also group 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 adults' responses on children's vocalization type and of children's vocalization type on previous adults' responses. These findings are 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 to be diminished in ASD in two ways. First, children with autism produce fewer vocalizations, perhaps because of endogenous differences in motor skills (Amorosa, 1992), differences in action selection (perhaps related to premature prefrontal cortex development; Courchesne & Pierce, 2005), or differences in 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 opportunities for the child to learn from contingent social feedback (see also Leezenbaum et al., 2013; Tamis-LeMonda et al., 2001; and Yoder, 1999).

Second, responses of adults interacting with children with autism, compared with responses of adults interacting with TD children, are less contingent on the children's vocalizations 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 their children's behavior (Yoder, 1999). A difference in adults' learned expectations would be consistent with there being a similar social feedback loop shaping adults' behaviors. Although investigating this possibility was outside the scope of the present study, it should be possible to test it by looking at the contingency of adults' responses on their children's previous responses to adult responses.

The reduced contingency of adults' responses to children with ASD could also be due to lower quality of the children's speech-related vocalizations. In this study, we considered only whether or not a child's vocalization contained speech-related material, but voice quality, the words and phrases in a vocalization, its prosody, and other factors likely also play a large role in determining the likelihood of an adult responding. Regardless of the reason, the reduction in adults' contingent responding to children with ASD means that they have reduced opportunities to learn about the social effects of their vocal behavior.

Third, the social feedback loop could be diminished for children with autism if they have reduced ability to attend to and make use of adults' contingent social responses (Dawson et al., 2004; Karmiloff-Smith, 1998; Klin, 1991; Mundy & Crowson, 1997; Mundy & Neal, 2000). Such differences from TD children could ultimately stem from overgrowth in prefrontal and other cortical brain regions during the 1st year of life (Courchesne et al., 2011; Hazlett et al., 2011), which might be expected to affect learning from environmental contingencies (Thompson-Schill et al., 2009). We did not find any statistically significant differences between groups in the contingency of children's vocalization types on previous adult responses, which may reflect a true lack of a group difference or merely a lack of sensitivity of the measure.

Successful interventions targeting adult responding (National Research Council, 2001; Yoder & Stone, 2006) 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 parents' responses on the speech relatedness of their children's vocalizations is a likely result. Even if parents increase their responsiveness indiscriminately to all types of their children's vocalizations, including crying, fussing, babbling, singing, and speech, this can be expected to increase the child's overall vocalization rate, thereby increasing the number of iterations of the social feedback loop (learning opportunities) the child experiences. In some cases, parent-focused intervention appears to attenuate growth of children's communication (Carter et al., 2011); this could be the result of disrupting parents' natural contingent responding to their children's 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 we have reported here.

In addition to differences between the TD and ASD groups, we observed differences related to age and maternal education. Proportional frequency of speech-related vocalization, overall levels of interaction, and contingency of adults' responses on children's 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 in vocal interactions. 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 that SES has significant effects on children's speech and language development as a result of differences in parent-child interactions (Greenwood et al., 2010; Hart & Risley, 1995; Hoff, 2003).

In summary, we propose that a social feedback loop supports speech development: Adults respond contingently to children's speech-related vocalizations, and the characteristics of children's vocalizations are in turn contingent on adults' previous 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 reveal two ways in which ASD appears to reduce the effectiveness of the social feedback loop: (a) The disorder reduces the amount of vocal material that the child produces and that is therefore available for adults to respond to, and (b) the disorder is associated with decreases in the extent to which adults' responses are contingent 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.

Author Contributions

A. S. Warlaumont designed the study with input from J. Gilkerson, J. A. Richards, and D. K. Oller. J. Gilkerson and J. A. Richards acquired the audio recordings and demographic information. A. S. Warlaumont and J. A. Richards analyzed the data. A. S. Warlaumont, D. K. Oller, and J. Gilkerson interpreted the results. A. S. Warlaumont wrote the manuscript, and D. K. Oller, J. Gilkerson, and J. A. Richards contributed revisions. All the authors approved the final version of the manuscript for submission.

Acknowledgments

We would 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 manuscript.

Declaration of Conflicting Interests

J. A. Richards and J. Gilkerson are employees of the LENA Research Foundation. K. Oller is an unpaid member of LENA Research Foundation's Scientific Advisory Board. The remaining authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This work was supported by a Department of Energy Computational Science Graduate Fellowship (DE-FG02-97ER25308), the National Institute on Deafness and Other Communication Disorders (R01 DC011027), the Plough Foundation, and the LENA Research Foundation. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

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