It's Time: Quantifying the Relevant Timescales for Joint Attention

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Abstract

The study of the coordination of attention, a term called joint attention (JA), has resulted in a better understanding of the dynamics and development of communication. Despite the important insights gained from studying JA, there is little consensus regarding the specific components that are included in operationalizing JA. The present work explored a parameter space of JA during a dyadic naturalistic toy play task between 9-month-old infants and their parents. We systematically measured the temporal properties of two components commonly used to operationalize JA: the duration of continuous alignment of parent and infant visual fixations and the flexibility of fluctuations of attention. The results show that very brief bouts of JA are important predictors for vocabulary development. The results from this work provide new insights into the specific properties used to operationalize JA and point to the importance of considering multiple timescales of behavior that make up JA.

Keywords: joint attention; communication; development; language development; methodology

Introduction

Human interaction consists of behaviors that occur across multiple timescales. When an infant interacts with a parent, physiological rhythms are coordinated within a 1s timescale (Feldman, Margoi-Cohen, Galli, Singer, & Louzoun, 2011), vocalizations at a 3s timescale (van Egeren, Barratt, & Roach, 2001; Harder et al., 2015), and leader-follower dynamics of vocalizations fluctuate across a 10s-temporal window (Abney, Warlaumont, Oller, Wallot, & Kello, 2016). Infants and their parents also coordinate their attention onto objects, a coordinative behavior called joint attention. The achievement of joint attention emerges early in the first year of life (Scaife & Bruner, 1975), and has been shown to be a fundamental component of communicative skills ranging from the development of language to social competencies (Mundy & Newell, 2007). The main goal of the current paper is to determine the relevant timescales for joint attention during infancy.

The empirical study of joint attention was initiated by the seminal work of Scaife and Bruner (1975) observing that infants could follow the direction of a partner's gaze within the first year, and that this behavior increased in frequency with age. Since Scaife and Bruner's original findings, decades of research have led to important theoretical and empirical contributions to areas of psychology ranging from basic questions and connections about attentional processes (Corkum & Moore, 1995; Mundy, Card, & Fox, 2000), to whether or not joint attention is critical for language development (Baldwin, 1995; Tomasello, 1988; Akhtar & Gernsbacher, 2007), and has led to proposals about the origins of theory of mind (Baron-Cohen, 1991) and communication (Tomasello, 2010).

Table 1: Summary of an abbreviated literature review of studies investigating the relationship between joint attention and language. Note: u.r. = under review. ^{n}=semi-naturalistic play paradigm. ^{ht}=head turn paradigm. Age in is months. T = timescale (s)

Author	Year	N	Age	T
Bakeman & Adamson^{n}	1994	28	6-18	3
Brooks & Meltzoff^{ht}	2005	96	9-11	6.5
Brooks & Meltzoff^{ht}	2008	32	10-11	6.5
Carpenter et al.^{n}	1998	24	9-15	3s
Morales et al.^{n}	1998	22	2-18	NA
Mundy, Sigman, & Kasari^{n}	1990	45	33	NA
Tomasello & Farrar (Exp. 1)^{n}	1986	24	15-21	3
Tomasello & Farrar (Exp. 2)^{n}	1986	10	17	3
Tomasello & Todd^{n}	1983	6	12-13	3
Yu, Suanda, & Smith^{n}	u.r.	26	9	.5

Although the overall consensus is that joint attention is an important ability, there is less agreement and consistency regarding how joint attention is defined and operationalized. For example, in Scaife and Bruner's (1975) original work, a positive joint attention behavior was coded if an infant (a) looked in the same direction as the experimenter without (b) intervening looks elsewhere within (c) 7s of the experimenter's look. In another example, Bakeman and Adamson (1984) coded behavior as a coordinated joint engagement state if the infant (a) actively coordinates his or her attention with another person and an object for (b) a particular duration with (c) only brief attention shifts to other objects for less than 3s. Finally, Tomasello and colleagues (Tomasello & Todd, 1983; Tomasello & Farrar, 1986) defined joint attention as when (a) infant and parent both visually attended to the same object for (b) at least 3s with (c) only brief looks elsewhere. Table 1 provides an abbreviated review of the timescales used to operationalize joint attention for studies focused on the relationship between joint attention and language.

In free-flowing parent-infant everyday interaction, joint attention is embedded in a stream of free-flowing activity in which parents both react to and attempt to control toddlers' behaviors and in which toddlers react to, direct, and sometimes ignore parents as they pursue their own goals. In those naturalistic contexts, we know that adults generate on average 3 eye fixations per second (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003) and we also know, from our recent head-mounted eye tracking studies, infants generate lots of short looks in toy play (Yu & Smith, 2016). That means the exquisite real-time "dance" of social interactions require effective adjustments within the dyad and socially coordinated shifts in attention have to be resolved in fractions of a second. In this context, it is possible that joint attention spans multiple timescales, displaying important variability at short timescales and also at longer timescales.

The specific goal of the current paper is to investigate the relevance of two key parameters used to operationalize joint attention that have varied considerably across research groups: the duration of continuous alignment of parent and infant visual fixations and the flexibility of fluctuations of attention. We refer to the former parameter as *minimum joint duration* and the later parameter as *minimum duration*. For minimum joint duration, we varied the duration to estimate joint attention across micro-level (e.g., 500ms) and macro-level (e.g., 10s) timescales. We focused on two aspects of this manipulation. First, we investigated how properties of joint attention, like mean duration, frequency, and proportion, varied across the minimum joint attention dimension. Importantly, we were also interested in how minimum joint duration affected how many dyads in our sample exhibited joint attention at a particular timescale. For example, it is possible that some infant-parent dyads do not exhibit any macro-level joint attention bouts, which would require us to omit them from subsequent analyses. For minimum duration, we first kept the parameter fixed at 0ms to simulate coding schemes that only identified a JA bout as continuous visual alignment on a target object with no looks elsewhere (Study 1) and then manipulated the parameter to allow for brief fluctuations of attention less than 300ms (Study 2).

Second, we asked how different values of minimum joint duration impacted the predictive value of joint attention. Previous research has observed that joint attention correlates with concurrent – and predicts future – vocabulary size (Baldwin, 1995; Tomasello & Farrar, 1986; Tomasello & Todd, 1983; Smith et al., 1988; Carpenter et al., 1998; Morales et al., 2000; Mundy, Sigman, & Kasari, 1990). Therefore, to determine how minimum joint duration affects the predictive value of joint attention for vocabulary size, in Study 3, we estimated joint attention for different values along the minimum joint duration dimension for 9-month infants and their parents, and tested whether joint attention across various timescales predicted future vocabulary size.

Methods

Participants

26 parent-infant dyads participated (15 female and 11 male). The mean age of infants was 9.21 months (*SD*=0.23). Parent reports of vocabulary were collected three and six months later when the infants were 12 months and 15 months.

Stimuli

Six toys (car, cup, and train; duck, plane, and boat), organized into two sets of three were used. Each toy in the two sets had a unique uniform color (red, blue, green).

Stimuli

Parents and their infants sat across from each other at a table (61cm x 91cm x 64cm). The infants sat in a custom high-chair and the parents sat on the floor. Both infants and parents wore head-mounted eye trackers (positive science, LLC). The head-mounted eye-tracking system includes two cameras: (1) An infrared camera that is placed just below and is pointed to the right eye that records eye images, and (2) A scene camera that is placed low on the forehead and is pointed outwards captures the user's first-person view (90° visual field). Each eye tracking system recorded egocentric-view video and gaze direction (x-, y-coordinates) in that view, sampled at 30Hz. Another camera (30Hz) was mounted above the table and provided a bird's eye view of the dyadic interaction (see Yu & Smith (2013) for additional technical details).

Procedure

Parents and infants were fitted with the eye-tracking gear (see Figure 1). Once the eye-tracking gear was securely affixed to the participants, a calibration phase was completed. To collect calibration points for each eye-tracker, an experimenter directed the infant's attention toward a toy that was only used for calibration while another experimenter recorded the moment the child attended to the location of the toy. This procedure was repeated 15 times with the calibration toy played in various locations on the tabletop. A similar procedure was used to calibrate the parent's eye tracker. The calibration procedure took approximately five minutes.

Once the calibration phase was complete, an experimenter placed one of the object sets on the table and the first play trial began. During object play, parents were instructed to engage with their infant as they naturally would. After approximately 60 seconds of play, an experimenter swapped out the objects with the second set of objects, and the second trial began. This procedure was repeated and dyads completed up to four trials for a total of six minutes of play. Not all dyads completed the full play session. Twenty-four dyads completed all four trials and two dyads completed three trials, for a total average playtime of five minutes, eight seconds.

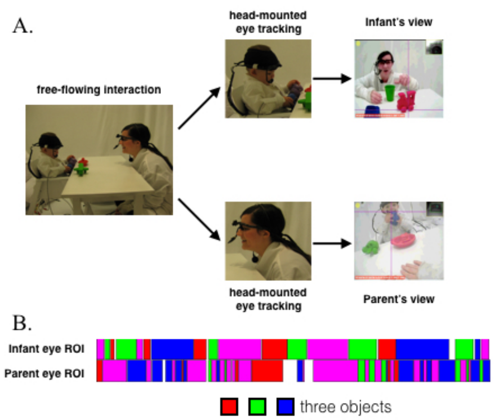

Figure 1: (A) A dual eye-tracking set-up. (B) Sample infant and parent ROI streams.

Data Processing

Eye-tracking software yielded scene camera footage with crosshairs superimposed, this footage was then sampled at a rate of 30 frames per second. Using an in-house coding program, trained coders annotated frame-by-frame the target of gaze. Three regions of interest (ROIs) were defined for the three objects. ROIs were manually coded frame-by-frame from a first-person view video. An ROI was annotated when a cross-hair overlapped on any portion of an object or face. To assess reliability, a second coder coded a randomly-selected 10% of the frames with 95% agreement.

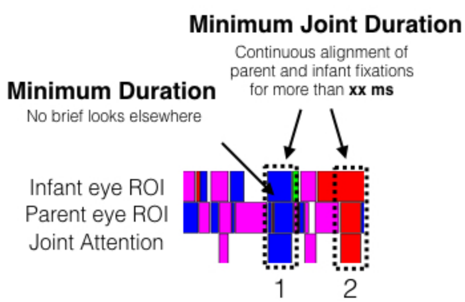

Figure 2: Operationalizing joint attention bouts using minimum duration and minimum joint duration.

Joint Attention Parameters

Two parameters were used to determine joint attention: minimum joint duration and minimum duration (see Figure 2). Minimum joint duration is the temporal duration of continuous alignment of parent and infant fixations on a particular object ROI. Minimum duration is the temporal duration of brief looks elsewhere other than the joint attention ROI, e.g., another object, partner's face. Previous research has incorporated this component into various coding schemes, sometimes allowing for brief looks elsewhere, and for other coding schemes, not allowing the flexibility of brief looks. For Study 1, we keep this parameter fixed at 0ms to not allow for brief looks elsewhere. In other words, all joint attention bouts estimated for this study only included simultaneous and continuous fixations from infant and parent. For example, in Figure 2, Bout 1 (blue object) would not be considered a JA bout because there is a brief look from the parent to the infant's face (pink). Bout 2 (red object) would be considered a JA bout because (1) the infant's and parent's fixations were on the same object (red object) for longer than a particular duration set in our parameter exploration and (2) the fixations were continuous with no brief fixations elsewhere.
In Study 2, we manipulated the minimum duration parameter to equal either 0ms or 300ms. To return back to the example in Figure 2, when minimum duration equals 300ms, Bout 1 (blue object) would now be considered a JA bout because the brief look from the parent to the infant's face (pink) is shorter in duration than 300ms.

Exploration of Joint Attention Parameter Space

To explore the parameter space of minimum joint duration, we created six different temporal durations for minimum joint duration (500ms, 1s, 2s, 3s, 5s, and 10s). The other parameter we manipulated was *minimum duration*, and varied this parameter as either 0ms or 300ms. In Study 1, we fixed the minimum duration parameter to 0ms, and explored the minimum joint duration parameter across all six duration. In Study 2, we explored a combination of a subset of the minimum joint duration parameter (500ms and 1s) and the minimum duration parameter (0ms and 300ms).

Properties of Joint Attention Bouts

In Study 1, we estimated joint attention bouts across the minimum joint duration parameter space for each of the 26 infant-parent dyads. Thus, for each dyad, we had 6 joint attention streams. In Study 2, we estimated joint attention bouts across the limited minimum joint duration parameter and the minimum duration parameter, equating to 4 joint attention streams across the parameter space combinations. For each joint attention bout stream, we estimated three properties: proportion (% of time in joint attention), frequency (rate/min), and average bout duration. To determine how many *dyads with at least one joint attention bout* in each parameter space value, we calculated a parameter-level measure as the percentage of the sample (26 dyads) that yielded at least one joint attention bout in a particular parameter value. In Study 3, we explored how joint attention proportion estimates across the minimum joint duration parameter space at 9-months of age predicted vocabulary size at 12 and 15 months of age.

Vocabulary Size

Infants and parents returned to the laboratory at ages 12- and 15-month to complete the MacArthur-Bates Communicative Development Inventory (Fenson et al., 1994). We used total receptive vocabulary as our measure of vocabulary scores at each age.

Study 1

We first investigated the properties of joint attention bouts across parameter space. We conducted a linear mixed-effects model (Baayen, Davidson, & Bates, 2008) to examine the effects of minimum joint duration on the joint attention bout properties (proportion, frequency, and average bout duration). We included dyad membership as a random slope with the maximally permitted random intercept. Because only one dyad had at least one joint attention bout longer than the minimum joint duration parameter at 10s, we excluded the 10s duration from the minimum joint duration parameter in subsequent analyses (see Figure 3).

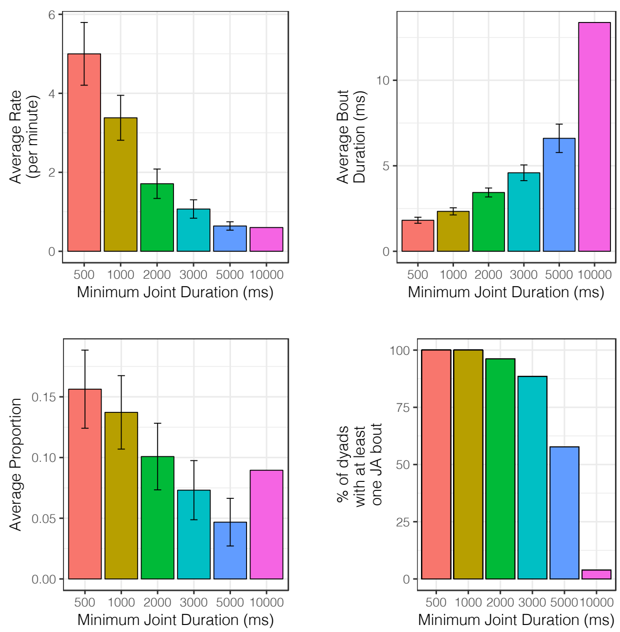

Figure 3: Joint attention properties across minimum joint duration parameters. Error bars reflect 95% CIs.

For joint attention rate, there was a significant effect of minimum joint duration (β=-.0009, *SE*= 0.00007, *p*<.001), suggesting that as minimum joint durations increased, the rate of joint attention bouts (per minute) decreased. When increasing the minimum joint duration parameter from the shortest duration reflecting the micro-level timescale, 500ms (M_{rate}=4.99, SE_{rate}=.39), to the frequently-used timescale in previous literature, 3000ms (M_{rate}=1.07, SE_{rate}=.11) (see Table 1; Bakeman & Adamson, 1994; Carpenter et al., 1998; Tomasello & Todd, 1983; Tomasello & Farrar, 1986), we observed a 78% decrease in JA bout rate.

As expected, for mean joint attention duration, there was a significant effect of minimum joint duration (β=.001, *SE*= 0.00003, *p*<.001), suggesting that as minimum joint durations increased, the mean duration of joint attention bouts increased.

Similar to what was observed for rate, for joint attention proportion, there was a significant effect of minimum joint duration (β=-.0001, *SE*= 0.00002, *p*<.001), suggesting that as minimum joint durations increased, proportion decreased. When increasing the minimum joint duration parameter from 500ms ($M_{proportion}$=.16, $SE_{proportion}$=.02) to 3000ms ($M_{proportion}$=.07, $SE_{proportion}$=.01), we observed a 53% decrease in JA proportion.

Calculating the percentage of dyads with at least one joint attention bout for a particular parameter space value provides a metric of how the sample size changes as a function of parameter value choices. Considering that investigations of joint attention utilize properties of joint attention bouts, we interpret this value below 100% for a particular combination to be suboptimal for the study of joint attention. Inspection of these estimates yielded some important observations. Estimates decreased as the duration of the minimum joint duration parameter increased. At 2s, the amount of dyads with at least one JA bout dropped below 100% and at 5s, only approximately 50% of the sample had at least one joint attention bout. This is an important observation because it points to a particular timescale, 2-3s, when the behavior of interest, joint attention, does not occur for some dyads in a sample.

We have established that after a particular timescale, 2-3s, the amount of dyads producing at least one bout of joint attention drops considerably with increases in the minimum joint duration parameter.

Study 2

To investigate the potential combinatory effects of both minimum joint duration and minimum duration, we estimated JA bouts across the minimum duration parameter (0ms and 300ms) and a subset of the minimum joint duration parameter dimension (500ms and 1000ms). Our parameter space therefore consisted of 4 possible combinations of the two parameters. We chose these parameters because (1) in Study 1, we observed 100% of the dyads had at least one JA bout for the 500ms and 1000ms minimum joint duration values and (2) 300ms as a value for the minimum duration parameter has been used in previous research to allow for flexibility in the fluctuations of attention (Yu & Smith, 2013, 2016).

Consistent with Study 1, for joint attention rate, there was a significant effect of minimum joint duration (β=-.0004, *SE*= 0.00003, *p*<.001), suggesting that as minimum joint durations increased, rate of joint attention bouts increased. There was no significant effect of minimum duration (β=.0001, *SE*= 0.0004, *p*=.76) nor was the interaction significant (β=.0000001, *SE*= 0.0000006, *p*=.78), suggesting, despite allowing for brief attentional flexibility (minimum duration=300ms) compared to no flexibility (minimum duration=0ms), joint attention rate remained the same (see Figure 5).

Mean joint attention duration increased as minimum joint duration increased (β=.002, *SE*= 0.0001, *p*<.001), but there was no significant effect of minimum duration (β=-.0002, *SE*= 0.0004, *p*=.75) nor was the interaction significant (β=.00000003, *SE*= 0.0000006, *p*=.56). Mean joint attention proportion decreased as minimum joint duration increased (b=-.0005, *SE*= 0.00004, *p*<.001), but there was no significant effect of minimum duration (b=.00005, *SE*= 0.0001, *p*=.74) nor was the interaction significant (b=-.00000005, *SE*= 0.0000002, *p*=.81).

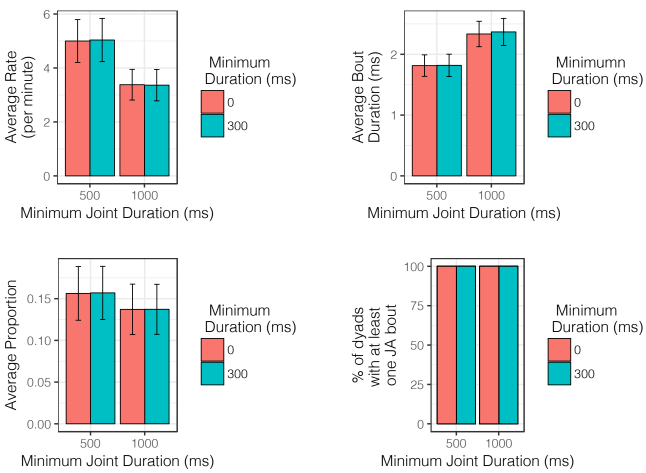

Figure 5: Joint attention properties across minimum joint duration and minimum duration parameters. Error bars reflect 95% CIs.

Study 3

We analyzed the relationship between joint attention proportion estimates across the minimum joint duration parameter space at 9-months of age and vocabulary size at 12 and 15 months of age. From the previous analyses, we know that increases in minimum joint duration lead to decreases in the amount of joint attention bouts and also the proportion of joint attention bouts. It is possible that even though joint attention proportion decreases, the overall variability still predicts vocabulary size. Alternatively, it is also possible that decreases in joint attention proportion also reduces the likelihood that the variability of joint attention proportion covaries with later vocabulary size. Table 2 shows the correlation results across parameter space values for joint attention proportion at 9 months and vocabulary size at 12 and 15 months. As observed in previous analyses, the amount of dyads with proportion estimates varies across the parameter space. Therefore, it is important to note the varying degrees of freedom of the correlations across the parameter space values.

There are a few important observations from this analysis. First, the pattern of correlations between joint attention proportion and vocabulary size does not vary across 12 months to 15 months. This suggests that the predictive value of joint attention at 9 months extends into the second year of life. Second, the results suggest that after exceeding a minimum joint duration of 3s, joint attention is no longer predictive of language development. This is an important finding because it strengthens the argument that the relevant timescales for joint attention, and subsequent predictive value for language development, include durations shorter than 3 seconds. We will discuss the implications of this result in the Discussion section.

Table 2: Summary of correlation coefficients (degrees of freedom in parentheses) between JA proportion and 12- and 15-month vocabulary size across the Minimum Joint Duration parameter.

Minimum Joint Duration	12 months	15 months
500ms	.58(24)***	.54(24)***
1000ms	.61(24)***	.56(24)***
2000ms	.50(23)***	.45(23)***
3000ms	.53(21)**	.53(21)*
5000ms	.18(14)	.16(14)
10000ms	-	-

Note. **p*<.05, ***p*<.01, ****p*<.001.

Discussion

The present study investigated the relevant timescales for joint attention in infant-parent naturalistic free-play. To answer this question, we explored a parameter space consisting of two frequently used components implemented to operationalize joint attention: minimum joint duration and minimum duration. Across three studies, we observed a collection of important results that provide insight into the consequences of choosing specific parameters for operationalizing joint attention. First, the observation of joint attention behavior drops precipitously when the duration of continuous alignment of parent and infant visual fixations (minimum joint duration parameter) extends longer than ~3s. Second, allowing for brief fluctuations of attention away from the target object (minimum duration parameter), does not appear to impact the overall properties of joint attention. Third, the predictive value of joint attention for language development reduces in strength when joint attention bouts shorter than 3s are omitted from analysis.

Perhaps the most important observation from this study was that when we only included joint attention bouts exceeding 3 seconds, the properties of joint attention changed significantly: rate and proportion of joint attention bouts were reduced by 50% or more. Furthermore, only including joint attention bouts exceeding a 3-second duration resulted in the loss of predictive value of joint attention for vocabulary size. Taken together, these results suggest that a purely macro-level approach to the study of joint attention can lead to a loss of important variability that captures the phenomenon of joint attention.

We also observed that the inclusion of a parameter that affords brief fluctuations of attention to parts of the visual environment other than the target object does not significantly affect the properties of joint attention. It is important to point out that we limited this analysis to only a subset of the minimum joint duration parameter in order to include all joint attention bouts longer than 500ms and 1000ms. It is possible that the inclusion of macro-level values of minimum joint attention (e.g., 500ms) and longer values of minimum duration – extending the duration of fluctuations of attention – would affect the joint attention properties beyond nominal differences. We plan to attend to this question in more detail in subsequent research.

Investigations of joint attention provide unique insights into the development and dynamics of human communication. The present study focused on an important methodological and theoretical question: what are the relevant timescales for joint attention? Our results, generated from a deductive technique to explore different areas of the parameter space of joint attention, suggest that the inclusion of micro-level temporal specifications of joint attention (e.g., <3s) is important for capturing a more vibrant picture of joint attention.

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