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Automated Measurement of Attachment Behaviors During the Strange Situation Procedure

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AUTOMATED MEASUREMENT OF ATTACHMENT BEHAVIORS DURING THE STRANGE SITUATION PROCEDURE

By

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Automated Measurement of Attachment
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Infant attachment security is typically measured with the Strange Situation Procedure (SSP) and experts then rate attachment-related behaviors (proximity-seeking, contact-maintenance, resistance and avoidance) in the two reunion episodes of the SSP. However, expert ratings are time-intensive and do not provide objective descriptions of infant behavior. Movement and audio data were collected using Kinect motion detection and LENA audio recordings during the SSP in order to evaluate the utility of automated measures as possible correlates of attachment behaviors. Results indicate that dyadic measurements of mother and infant position in the room, when combined with more infant-centered variables such as initial approach and crying, accounted for a significant proportion of the variance in expert ratings. In addition, there were strong associations between these objective features and dimensional measurements of attachment. This is the first application of automated measurement to attachment behaviors and provides insight into behavioral patterns previously captured exclusively via expert but subjective rating scales.

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CHAPTER 1: INTRODUCTION

Early attachment refers to an infant's expectations concerning the availability of his or her attachment figure. Attachment security indexes an infant's ability to be comforted by a parent when distressed, which in turn maximizes the infant's opportunities for exploring the environment. Infant attachment security is a centerpiece of healthy social and emotional development (Kochanska & Kim, 2013; Sroufe, 2005, van IJzendoorn, Schuengel, & Bakermans–Kranenburg, 1999). However, there is not an objective, standardized description of the behaviors that define early attachment security. Researchers instead rely on qualitative descriptions and rating scales to inform the attachment classification process. In this project, we applied objective measurement techniques to the Strange Situation Procedure, a gold-standard measure of infant attachment, in order to find objective descriptions of behavior associated with expert measurement.

Attachment and the Strange Situation Procedure

Early attachment security is most frequently assessed in the Strange Situation Procedure (SSP) (Ainsworth, Blehar, Waters, & Wall, 1978; van IJzendoorn & Kroonenberg, 1990). In the SSP, the infant is separated from and reunited with his or her parent twice within a twenty minute play session. Trained experts then rate the infant's proximity-seeking (approaching parent), contact-maintenance (remaining close to parent), resistance (to contact with parent), and avoidance (ignoring or moving away from parent) behaviors during the two infant-parent reunions. Each of these is measured on a 7-point Likert scale, which includes behavioral examples that anchor specific ratings (Ainsworth et al., 1978; Waters, 2002). Ratings of proximity-seeking index the intensity

and persistence of the infant approaching the parent with the higher scores indicating that the infant purposefully moves toward the parent and achieves contact (Waters, 2002). Contact-maintenance is a rating of the infant's persistent effort to stay in close contact with the parent and unwillingness to end that contact during the reunion episodes (Waters, 2002). Resistance ratings capture fussy behavior such as pushing away from the parent, kicking or squirming when held, and angry crying. Infants high in resistance may also quickly alternate between seeking contact and rejecting it (Waters, 2002). Finally, avoidance ratings index how quickly, intensely, and for what length of time the infant attempts to avoid contact with the parent by engaging in behaviors like leaning away, turning the head or simply ignoring (Waters, 2002). All infants are also assigned a disorganization score on a 1-9 Likert scale which indexes the presence and frequency of unusual or contradictory behaviors including overt displays of fear, stereotypic movements, or freezing in place for an extended period of time (Main & Solomon, 1986).

The current study will focus on whether objective measures of infant and parent behavior in the SSP can predict Likert-scale expert ratings. As an outgrowth of the ratings system, researchers have applied various algorithms to the Likert scales in order to create a continuous measure of attachment behaviors (Richters, Waters, & Vaughn, 1988; Fraley & Spieker, 2003). On the basis of taxometric analyses data, Fraley and Spieker (2003) argued that attachment behavior falls along two dimensions: approach versus avoidance behaviors (composed of proximity-seeking, contact-maintenance and avoidance scores) and degree of resistance (composed of resistance and disorganization scores). The current study will apply objective measures of movement and audio in the SSP to predict these dimensions as well as individual ratings.

Both the training of expert raters and the classification process itself is resource intensive and does not produce a transparent description of attachment behaviors. Rather, the complexity of infant and parent behaviors in the SSP are summarized in the 1-7 Likert scales. Objective measurement tools provide a unique opportunity to quantify infant and parent behaviors in the SSP and capture the depth of behavioral data summarized in expert rating scales.

Objective measurement can extend attachment theory's grounding in the careful description of infant-parent interaction (Ainsworth et al., 1978; Bowlby, 1982). It may elucidate our understanding of the behavioral factors which impact expert ratings of proximity-seeking, contact-maintenance, resistance and avoidance. For example, despite attachment theory's insistence on the centrality of interaction, parent behavior in the SSP is considered to be irrelevant to infant attachment classification. Objective measurement of the coordination between infant and parent movement could suggest the pervasive importance of interaction and reveal an unexplored source of variance in infant attachment ratings (Behrens, Parker, & Haltigan, 2011).

Objective Measurement and Attachment

To objectively capture infant and mother behavior in the two reunions, we used Microsoft Kinect and the Language ENvironment Acquisition (LENA) audio recording and analysis software. The Kinect is an economical, widely-available sensor that incorporates both a depth sensor and RGB video camera. The depth sensor captures continuous 3D information about the position and orientation of individuals in space. The combination of the 2D video and the 3D depth information allows for modeling the movement of people and objects in space (Sivalingam et al., 2012). Kinect has been used to examine social interactions in a variety of contexts, including motor coordination in

conversational settings (Avril et al., 2014), the development of gestures (Nagai et al., 2012) and parent-infant contingent responding (Fukuyama et al., 2015; Leclere et al., 2016; Nagai et al., 2012; Rehg, 2013). All of these studies focused on seated face-to-face interaction rather than free movement in a room. In this study, we deployed a suite of four Kinect cameras to capture the location of the infant and parent during the SS reunions.

When rating behavior during the SSP, expert raters not only attend to infants' movements but also their vocalizations. The amount of crying during both the separation and reunion episodes of the SSP is noted and is used to quantify the infant's level of distress and how quickly he or she is comforted by the parent (Ainsworth, 1979). The LENA recorder collects audio information which is then classified by LENA software, yielding measures of infant non-speech-related vocalizations (e.g. crying) (Richards, Gilkerson, Paul & Xu, 2008; Oller et al., 2010). In this study, infant crying was captured with LENA recorders in order to objectively measure the duration of infant distress in the SSP.

Current Study Aims

Automated movement tracking and audio analysis provide a matrix of objective indices that can be used to better understand behavior during the SSP. This study will measure the relationship between expert ratings of attachment behaviors and objective measurement of movement and audio recordings. Kinect and LENA measures will be used to generate a set of objective features. We will then examine the univariate and multivariate associations between those objective features and the expert ratings and dimensional scales of attachment behavior. Some of these objective measures are inherently dyadic (e.g. contact time between parent and infant) while others are infant-

centered (e.g. infant approaching the parent), and we will examine to what extent each feature contributes to the expert ratings. Finally, we will also employ a bottom-up data driven approach that uses all objective features to predict expert ratings and dimensional measures and allows us to explore how closely the objective measures can replicate the expert ratings and dimensional measures.

CHAPTER 2: METHOD

Participants

34 infant-parent dyads completed the SSP around the infants' first birthday (*M* age = 11.90 months, sd = 0.71; 20 male infants). While both mothers and fathers were eligible for the study, only mothers participated in this sample. Ethnically, 64% of the sample identified as Hispanic or Latino. The racial composition of the sample was 80% Caucasian and 20% Black.

Protocol

The Strange Situation was conducted following standard procedures (Ainsworth et al., 1978)**.** It consisted of eight three-minute episodes, including two separations from the mother, each followed by a reunion. Separations (but not reunions) were curtailed if the infant was highly distressed (e.g., 60 seconds of crying) (Waters, 2002). Episodes 5 and 8, referred to in this study as Reunion 1 and Reunion 2, are the focus of experts' rating of attachment behaviors (Ainsworth et al., 1978; Waters, 2002), and the focus of this study. The SSP was conducted in a lab space (3.15 m x 3.45 m x 2.4m room) equipped with four Microsoft Kinect sensors and 2 Elmo PTC-400C PTZ Cameras which recorded to DVD in an associated control room (see Figure 1). Expert raters used the DVD recording for behavioral ratings of the SSP.

Measures

Expert ratings. Following the SSP, an experienced rater trained by L. Alan Sroufe and Elizabeth Carlson who had successfully passed the Minnesota attachment reliability test reviewed video of the protocol and rated four infant attachment behaviors in the two reunion episodes: proximity-seeking (approaching mother), contact-maintenance (staying close to mother), resistance (to contact with mother), and avoidance

(ignoring or moving away from mother). The expert rater also rated the infant's level of disorganization in his or her behavior. Disorganization is rated on an overall 9-point Likert scale that applies to all periods during the SSP where infant and mother are together. On this scale, higher scores indicate greater disorganization, manifesting in contradictory behavior patterns, stereotypies, freezing, and or apprehension regarding the parent (Main & Solomon, 1986).

Dimensions of attachment behavior. To generate continuous measures of attachment behaviors, we combined the five rating scales into two dimensions: approach/avoidance and resistance/disorganization (Fraley & Spieker, 2003). Approach/avoidance was calculated by taking the mean of proximity-seeking, contact-maintenance and the inverse of avoidance scores. Resistance/disorganization was calculated by standardizing resistance and disorganization ratings using Z-scores and taking the mean (Fraley & Spieker, 2003). Associations between the five Likert scales (proximity-seeking, contact-maintenance, resistance, avoidance, disorganization) and the two dimensions (approach/avoidance, resistance/disorganization) in each reunion are reported in Table 1.

Reliability. For a subset of the infants (N=21), a second Minnesota-trained and reliable rater completed independent ratings and classification. There was an exact match between raters for the A, B, and C security classifications. Out of the 34 infants in the study, 1 was classified as insecure-avoidant, 6 as insecure-resistant and 27 as securely attached. Absolute individual two-way mixed intraclass correlations for the behavioral ratings indicated they were highly reliable for proximity-seeking (Reunion 1 *ICC*=.89; Reunion 2 *ICC* =.88), contact-maintenance (Reunion 1 *ICC* =.91; Reunion 2 *ICC* =.87),

resistance (Reunion 1 *ICC* =.95; Reunion 2 *ICC* =.88), and avoidance (Reunion 1 *ICC* =.74; Reunion 2 *ICC* =.82), but lower for the disorganization score (*ICC* = .42).

Movement tracking. Kinect RGB videos were recorded with spatial resolution of 640 x 480 pixels and temporal resolution of 30 frames-per-second. In post processing Kinect video and depth recordings were fused, projecting multiple Kinect measurements into a single 3D map to enhance localization accuracy (see Figure 1.). This was accomplished by finding common point correspondences between images, and computing 3D rigid transformation, using the Singular Value Decomposition method (Ciptadi, 2016). The Kinect sensor addresses environmental variation such as changes in lighting conditions (Huang, Yao, Wang, & De La Torre, 2014) by incorporating depth-based measurements which provide substantial robustness in comparison to conventional motion tracking methods based on 2D imagery (Sivalingam et al., 2012).

Mother's and infant's heads were tracked in 3D space during the two reunions using a user in the loop system (Ciptadi, 2016). Tracking for infant and parent occurred separately and were synchronized (see Appendix A). Based on a bounding box drawn by the user, we first obtained a 3D template of the infant or parent's head and computed an initial estimate of the head's location in the room. Movement of the infant or parent's head was then tracked throughout the reunion using a standard linear Kalman filter with a constant velocity assumption (Ciptadi, 2016). Corrections to the tracker were made by the user when occlusion of the infant or parent's head or detection errors occurred (approximately 7 corrections per minute of tracking). Detection error is defined as times when the bounding box drifted to the point where it no longer included at least 60% of

the head. We employed standardized procedures to interpolate infant and mother position when either could not be tracked (see Appendix A).

Following tracking, infant and mother position in 3D space was used to continuously calculate the overall distance between them, the velocity of each partner's movement, and the amount of time infant and mother were in contact. Contact was defined as occurring when the infant's head was within 80cm of the mother's, approximately within arm's length. Carrying of the infant by the parent occurred when the infant was more than 90cm above the floor. Using these metrics of distance, velocity, and contact, additional theoretically-informed measures of attachment-related behavior were calculated (Table 2). These features included both dyadic and infant-centered patterns of behavior with expected associations with expert ratings of attachment behavior. Dyadic features were mean distance, the average distance (in cm) between infant and mother during the reunion; contact duration, the amount of time (in seconds) the infant was in contact with the parent; and time held, the amount of time the infant was carried by the parent. Infant-centered variables were contact initiation, a count of how frequently the infant initiated contact with the parent; and initial approach, the sum of the infant's velocity (m/sec) in the first five seconds following the mother's entrance into the room. Initial approach values were negative when the infant's movement away from the mother was greater than the infant's movement toward the mother.

Audio analysis. Audio from all infants was captured using Language ENvironment Analysis (LENA) recorders. The resulting audio files were analyzed using LENA signal processing software which distinguishes child speech and non-speech vocalizations from other ambient noise in the environment (Oller et al., 2010). The

majority of the infants (N=24) were outfitted with LENA recorders during the SSP which were carried in a specially designed vest worn by the infant. For the additional 10 dyads, LENA data was captured from the audio track of SSP audiovisual recordings at a rate of 44.1 kHz. In the case of the SSP, where infants are frequently distressed, we assumed that the majority of the audio coded as infant non-speech vocalizations originated from crying, rather than laughter or other vegetative sounds. In order to confirm that assumption, manual coding of the two reunions from 26 of the recordings was conducted. Coders naïve to the results of the LENA analysis listened to the recordings and calculated the proportion of time the infant spent fussing or crying. Individual absolute agreement intraclass correlations revealed the non-speech-related vocalization variable from LENA was highly associated with manual codes of infant crying/fussing (Reunion 1 = .87 and Reunion 2 = .94).

CHAPTER 3: RESULTS

The association between expert ratings and objective features was examined in three steps. First, we determined which objective features had the highest univariate associations with the expert ratings and the dimensional measures. Next, we conducted linear regressions to identify pairs of features that uniquely and significantly predicted expert ratings and the dimensional measures. Finally, we employed a bottom-up approach to linear regression which included all objective features as predictors to determine how closely we were able to replicate expert ratings and dimensional measures using all available information.

Univariate associations between expert ratings and objective features

The four expert ratings of attachment behaviors (proximity-seeking, contact-maintenance, resistance, and avoidance) were significantly correlated with multiple objectively measured features (see Table 4). In order to determine which features were most highly and consistently associated with each rating, an average of the correlations in each reunion was calculated (represented here by M_r). Each univariate correlation aggregated below was significant at or below $p \leq .05$ (see Table 4).

Expert proximity-seeking ratings were most highly correlated with the initial approach (M_r =.48) and contact initiation (M_r =.47) objective features. The initial approach and contact initiation features were themselves moderately correlated (M_r =.33). Infants who scored high in proximity-seeking were faster to seek out their mothers at the beginning of each reunion and were more likely to seek and achieve contact with her throughout the reunions.

Expert contact-maintenance rating was most highly correlated with the contact duration (M_r =.77) and mean distance (M_r =-.75) objective features. The contact duration

and mean distance features were themselves highly correlated (M_r =-.87). Infants who scored high in contact-maintenance, spent more time in contact with their mothers and stayed closer to her throughout the reunion.

Expert resistance rating was most highly correlated with the infant crying during the two reunions (M_r =.64) and contact duration (M_r =.57) objective features. The infant crying and contact duration features were themselves moderately correlated (M_r =.42). Infants who scored high in resistance fussed and cried for a longer portion of the reunions and spent more time in close contact with the mother.

Expert avoidance rating was most highly correlated with the contact duration (M_r =-.53) and amount of crying that occurred outside of the reunion (M_r =-.50) objective features. The contact duration and crying outside of the reunion features were themselves highly correlated (M_r =-.62). Infants who scored high in avoidance spent less time in contact with the parent and exhibited less distress outside of the reunion episodes.

To determine which objective features were most associated with all four expert ratings across the two reunions, we also calculated an average of the correlations across the expert ratings of each reunion. The contact duration objective feature had the highest overall association with the four expert ratings (M_r =.56), followed by mean distance (M_r =.54), and the amount of crying that occurred outside of the reunions (M_r =.45). These three features, contact duration, mean distance and crying outside of the reunion, were moderately to highly correlated with expert ratings in both reunions, with the exception of proximity-seeking in the second reunion (see Table 4).

Expert disorganized rating was most highly correlated with the amount of time the infant was held (M_r =-.24) and contact initiation (M_r =.19) objective features. The time

held and contact initiation features were not correlated (M_r =-.01). However, the individual correlations between disorganization and these objective features were not significant. In fact, the only significant association of an objective feature with disorganization was contact initiation in the second reunion (r =-.40), although the correlation with this feature in the first reunion was low (r =.07). This suggests infant with higher levels of disorganization approached and achieved contact with their mothers less frequently, but only in the second reunion,

Correlations of objective features with the Fraley-Spieker dimensional measures of attachment behavior indicated that the dimension approach/avoidance was most highly associated with the initial approach (M_r =.79) and contact duration (M_r =.64) objective features. The initial approach and contact duration features showed a low correlation (M_r =.15). Infants who scored high on the approach/avoidance attachment dimension exhibited more immediate approach toward mother and stayed in close contact with her for more time. The dimension resistance/disorganization was most highly associated with crying during the reunions (M_r =.60), followed by crying outside of the reunions (M_r =.50). Objectively measured crying in and out of the reunions was highly correlated (M_r =.72). Infants who scored higher on the resistance/disorganization dimension cried more during both reunions and during the remainder of the SSP.

Predicting expert ratings and dimensions using multiple regression

Based on the univariate correlations, iterative linear regressions were used to determine the combination of unique features in each reunion which best predicted the variance in expert ratings of proximity-seeking, contact-maintenance, resistance and avoidance, as well as the variance in the dimensional measures of approach/avoidance and resistance/disorganization. Each linear regression contains the best set of predictors

of the expert rating for both reunions and each feature is a significant and unique predictor of the rating in that regression equation.

Proximity-seeking. In the first reunion, initial approach (B= .47, $t(34) = 3.56$, $p < .01$) and contact duration (B= .41, $t(34) = 3.13$, $p < .01$) significantly predicted proximity-seeking. Together, they explained a significant proportion of the variance in proximity-seeking ratings (R^2=.50, $F(2, 31) = 15.19$, $p < .01$). However, in the second reunion, only initial approach (B= .37, $t(34) = 2.29$, $p < .05$) was a significant and unique predictor of proximity-seeking (R^2=.19, $F(2, 31) = 3.72$, $p < .05$).

Contact-maintenance. In the first reunion, contact duration uniquely predicted contact-maintenance (B = .72, $t(34) = 5.80$, $p < .01$) and explained a significant proportion of the variance in contact-maintenance ratings (R^2=.51, $F(2, 31) = 33.61$, $p < .01$). In the second reunion as well, contact duration was a significant predictor of contact-maintenance (B = .81, $t(34) = 7.84$, $p < .01$; R^2=.66, $F(2, 31) = 61.52$, $p < .01$). There were no other features which, when combined in the regression equation with contact duration, produced a significant beta.

Resistance. In the first reunion, proportion of time spent crying in the reunion (B = .50, $t(34) = 3.60$, $p < .01$) and contact duration (B = .33, $t(34) = 2.39$, $p < .05$) significantly predicted resistance. Together, they explained a significant proportion of the variance in resistance ratings (R^2=.52, $F(2, 31) = 16.44$, $p < .01$). In the second reunion as well, both crying during the reunion (B = .48, $t(34) = 2.90$, $p < .01$) and contact duration (B = .48, $t(34) = 3.57$, $p < .01$) were significant predictors of resistance ratings (R^2=.53, $F(2, 31) = 17.01$, $p < .01$).

Avoidance. In the first reunion, initial approach (B = .-.32, t(34) = -2.22, p < .05) and contact duration (B = -.49, t(34) = -3.42, p < .01) significantly predicted avoidance. Together, they explained a significant proportion of the variance in avoidance ratings (R^2=.42, F(2, 31) = 11.08, p < .01). In the second reunion as well, both initial approach (B = .-.51, t(34) = -3.99, p < .01) and contact duration (B = -.47, t(34) = -3.67, p < .01) were significant predictors of avoidance ratings (R^2=.50, F(2, 31) = 15.37, p < .01).

Disorganization. We calculated the mean of the objective features from each reunion and used them as predictors for the single disorganization score characterizing infant-parent interaction throughout the SSP. The mean of time held over the two reunions, which had the highest mean univariate correlations with disorganization, was not a significant predictor of the disorganization score (B = -.26, t(34) = -1.54, p = .13; R^2=.07, F(2, 31) = 2.38, p =.13), nor was any other combination of objective features from the first and second reunions. As we learned from the univariate correlations, only contact initiation from the second reunion alone was a significant predictor of disorganization (B = .45, t(34) = 2.83, p < .01; R^2=.20, F(2, 31) = 8.03, p < .01).

Dimensional measures. The mean of the objective features from both reunions were also used as predictors of the approach/avoidance and resistance/disorganized dimensions. Contact duration (B = .641, t(34) = 5.45, p < .01) and initial approach (B = .30, t(34) = 2.58, p < .05) significantly predicted approach/avoidance. Together, they explained a significant proportion of the variance in the approach/avoidance dimension (R^2=.60, F(2, 31) = 23.02, p < .01). Infant crying during the reunions uniquely predicted resistance/disorganization (B = .62, t(34) = 4.46, p < .01) and explained a significant

proportion of the variance in the resistance/disorganization dimension values (R^2=.38, $F(2, 31) = 19.857$, $p < .01$).

Regressing expert ratings on all objective features

Another approach to the prediction of expert ratings combines all objective features into a regression equation. This approach indicates how closely the objective measures can replicate the expert rating process, and what proportion of the variance in ratings is captured by objective measures of behavior. This bottom-up, data-driven approach maintains all parameters that minimize the error between predicted and expert ratings without regard to the significance of individual parameters (Lawson & Hanson, 1995; Zeng & Ogihara, 2009).

Using linear regression, all objective features were combined in order to predict expert ratings in each reunion, as well as disorganization and the dimensional measurements . There were strong associations between objective measures and expert ratings (see Table 5), with R^2 values ranging from .40 to .72. When the unstandardized predicted values from these regression equations were compared to the actual expert ratings, the difference was, on average, less than a point on the original 7-point rating scale (Mean difference = .74; Mean sd = .61). The combination of objective features was also able to significantly predict disorganization scores (R^2=.50), with an average of one point difference between the predicted score and the actual score. The dimensional measures were also both well-explained by the combination of all objective features (approach/avoidance R^2=.71; resistance/disorganization R^2=.57). The difference between predicted score and actual was minimal for both (see Table 5). The combination of all objective features, including movement and vocalization data came moderately close to replicating expert ratings and the attachment dimension composite scores.

CHAPTER 4: DISCUSSION

This is the first application of automated measurement, of both movement and vocalizations, to the study of attachment behaviors in the SSP. The results reveal a strong association between objectively measured patterns of behavior and expert ratings of infant attachment behaviors in the SSP. We used a variety of methods to explore these associations. Here, we will discuss the candidate regression and univariate correlation approaches for each of the expert ratings, followed by the dimensional measures. Next, we will discuss the overall trends in infant-centered and dyadic objective features and their associations with the ratings and dimensional measures. Finally, we will consider how the inclusion of all objective features allowed us to most closely replicate the expert ratings and dimensional measures..

Correlation and regression correspondences between expert ratings and objective features

Proximity-seeking. Expert ratings of proximity-seeking were best explained by objective measures of initial approach, the overall distance the infant traveled in approaching the mother in the five seconds after she entered the room. In the first reunion, initial approach and total amount of contact time explained approximately half of the variance in proximity-seeking. This suggests that infants who covered more ground in approaching their mother and spent more time in close contact with her were rated higher in proximity-seeking. However, in the second reunion, with only initial approach as a unique predictor, only a fifth of the variance in proximity-seeking was explained.. Initial approach and contact initiation were highly associated with proximity-seeking scores; however, contact initiation did not significantly or uniquely predict proximity-

seeking when entered into a regression with initial approach. Both measures were themselves moderately correlated and are based on infant approach behavior.

The initial approach feature was designed to capture infant's initiation of the first contact with the parent, which is crucial to expert rating of proximity-seeking. As rated by experts, infants with high proximity-seeking scores "purposefully approach the adult" and "go the whole way" without delay, while lower scoring infants do not approach fully or may not move at all (Ainsworth et al., 1978, p. 343). Duration of contact is mentioned in the coding scheme as well, with high scoring infants maintaining contact with the parent for over 15 seconds (Ainsworth et al., 1978, pp. 343-344). These findings suggest the importance of quantitative measures of the distance approached the mother, sometimes buttressed by the amount of time the infant remained closed to the mother, in indexing perhaps the most crucial attachment behavior, proximity seeking.

Contact-maintenance. Expert ratings of contact-maintenance in both reunions were predicted by the objective contact duration feature, to the exclusion of any secondary objective feature. While contact-maintenance was highly associated with both contact duration and mean distance, those two objective features were themselves highly correlated and were not unique predictors when combined in a regression equation. There was a strong one-to-one correspondence between the amount of time infants and their mothers spent in contact and the expert rating of contact-maintenance; in the regression equations, contact duration explained half to two-thirds of the variance in contact-maintenance.

The expert contact-maintenance ratings instructions rely heavily on duration, and explicit cut-offs are articulated for specific ratings, e.g. contact time above two minutes is

rated as seven (Ainsworth et al., 1978). However, the ratings scale also includes infant behavior such as clinging, leaning into the parent or resisting being placed on the floor (Ainsworth et al., 1978), which were not captured by the current objective features. Despite the lack of fine-grained infant behavior measurement, the objective measure of contact duration coincides well conceptually (and moderately well with quantitatively), with expert measures of the degree to which infants maintain contact with the attachment figure.

Resistance. Expert ratings of resistance in both reunions were predicted by the objective features of infant crying during the reunions and contact duration. These were also the two features most highly associated with resistance ratings overall. This suggests that the duration of infant vocal distress and the duration of time spent in close contact with the mother were complementary markers of resistance. Objective measures of crying and contact duration predicted approximately half of the variance in resistance scores in each reunion.

In the expert rating instructions, highly resistant infants may tantrum with angry screaming and/or squirm or struggle against being held (Ainsworth et al., 1978). While the objective measures did not capture the relevant resistant behaviors evoked by the attachment figure's attempts at interaction, such as rejection of toys, objective measures of crying and contact duration were able to conceptually capture the more diffuse manifestations of resistance, such as angry screaming and alternate attempts to seek and reject contact.

Avoidance. Expert ratings of avoidance in both reunions were uniquely predicted by the objective features of contact duration and initial approach. Infants who scored

higher in avoidance spent less time near their mothers and approached her less or moved away from her more than other infants at the beginning of the reunion. The features with the highest correlations with avoidance were contact duration and infant crying outside of the reunions, such that infants who scored higher in avoidance were less distressed during the separations from their parent. However, when combined with contact duration, infant crying was not a unique predictor of avoidance in either reunion. The combination of initial approach and contact duration was the best predictor avoidance scores and accounted for close to half of their variance.

In the expert rating instructions, the infant's initial reaction to the mother's arrival in the room is crucial; infants who score high in avoidance ignore the mother upon her return or actively avoid her and then continue to ignore her throughout the reunion episode (Ainsworth et al., 1978). The contact initiation feature is then conceptually and empirically aligned with avoidance in the SSP reunions. However though contact duration predicted avoidance, contact time between the infant and the mother is not explicitly mentioned in the rating instructions (Ainsworth et al., 1978). Thus contact duration—a measure of dyadic proximity—may offer new insight into what expert ratings of avoidance measure.

Disorganization. While there were moderate to high associations between expert ratings of the original attachment behaviors (proximity-seeking, contact-maintenance, resistance, avoidance; Ainsworth et al., 1978) and objective features, the disorganization rating (Main & Solomon, 1986) was not well captured by objective measurement. Contact initiation in the second reunion was the sole significant predictor of disorganization and accounted for approximately one fifth of the variance in scores.

Disorganization is a complex rating scale, which incorporates a variety of behaviors, including movement, orientation, repetitive gestures and facial expressions, all under one umbrella scale introduced after the original four rating scales (Main & Solomon, 1989). It also incorporates behavior throughout the SSP while objective movement features were measured entirely during the reunion episodes. Eventual tracking of movement across the entire SSP incorporating fine-grained measurements of infant expression and gesture may aid in the prediction of disorganization.

Dimensional measures. The dimensional measures combined the individual expert rating scales along two continuous dimensions: approach/avoidance and resistance/disorganization (Fraley & Spieker, 2003). These are alternate methods of conceptualizing infant attachment which can be compared to classic attachment security classifications (i.e. secure, insecure-resistant, insecure-avoidant) which are a gestalt judgment informed but not determined by expert ratings (Ainsworth, 1979; Ainsworth et al., 1978; Main & Solomon, 1986; van IJzendoorn et al., 1999). As noted previously, several objective features were predictors of multiple expert ratings (e.g. initial approach with proximity-seeking and avoidance; contact duration with proximity-seeking, contact-maintenance, resistance, and avoidance). These overlaps across expert ratings suggest that a dimensional approach is warranted, as these ratings are associated with common objectively measured behaviors.

Given that the dimensional measures were generated from the individual expert ratings, their associations with objective features are similar. Contact duration and initial approach explained three-fifths of the variance in the approach/avoidance dimension, meaning that infants who scored highly on this dimension engaged in more approach of

their mothers at the beginning of the reunion and stayed in close contact with her for a longer time. Infant crying during the reunions explained two-fifths of the variance in the resistance/disorganization dimension, meaning that infants who scored higher cried for a greater proportion of both reunions. Crying outside of the reunion was also highly correlated with the resistance/disorganization dimension. However, given the low correlations between the objective features and disorganization scores, associations with resistance/disorganization likely reflect associations with resistance, not disorganization. These continuous scales have been suggested as a possible substitute for the traditional classification system (Fraley & Spieker, 2003) and they exhibited strong to moderate correlations with a small number of unique objective measures, approach magnitude, contact time, and time crying.

Infant-centered and dyadic objective features

Both infant-centered objective features, such as crying and initial approach behavior, and inherently dyadic features, such as contact time and the overall distance between parent and infant, were robust predictors of expert ratings and dimensional measures. Overall, contact duration was a significant unique predictor of the expert ratings in seven of the eight regressions (with the exception of proximity-seeking in the second reunion). When averaging across all four expert ratings, contact duration and mean distance were the most highly associated with expert ratings.

Contact duration and mean distance are jointly determined by infant and mother, throughout the two reunions. For example, mothers decide whether to pick the infant up when entering the room and determine how long to hold the infant. Infants decide whether to approach the mother when she returns and where in the testing room they choose to settle. Contact duration and mean distance's significant associations suggest

that the dyadic measure of mother-child interaction more accurately captured what experts rated during the SSP than the infant-centered variables on their own. However, when looking at individual scales, the importance of infant-centered variables becomes clearer. Initial approach was a significant predictor for both proximity-seeking and avoidance and infant crying was a significant predictor of resistance. In fact, the amount of crying that occurred outside of the reunion episodes was another variable which was highly correlated with all four scales. It was in the combination of dyadic and infant-centered features that we were able to get the clearest picture of expert ratings. These findings suggest that objective measurement techniques allow us to look beyond the 1-7 Likert scale summaries. They suggest the importance of dyadic interaction summarized in measures of infant-mother contact duration and infant-mother mean distance in capturing patterns of attachment.

Prediction of expert ratings and attachment dimensions using all objective features

The final analytic strategy involved predicting expert ratings and dimensions of attachment using a linear combination of all objective features (Lawson & Hanson, 1995; Zeng & Ogihara, 2009). In total, this included the five movement features (mean distance, contact duration, initial approach, contact initiation, and time held) and crying from both reunions, as well as crying in the remainder of the SSP. When these thirteen objective features were combined to predict expert ratings, they explained approximately one half to three-fourths of the variance in those scores (see Table 6). This is particularly noteworthy for the dimensional measures of attachment, approach/avoidance (R^2 = .71) and resistance/disorganization (R^2 =.57), which capture infant features of attachment behavior and may be used in lieu of the traditional classification system. On average, the predicted values came within one point of the actual scores. This suggests that the Kinect

and LENA features were accurately capturing infant and dyadic behaviors considered crucial to early attachment. It could be possible to run these objective measures on future SSPs and receive a close approximation of what an expert rater would note about the infant's behavior. However, this assumes that the regression equation is stable and generalizable to other samples. A larger sample is needed before this would be possible.

Limitations and implications

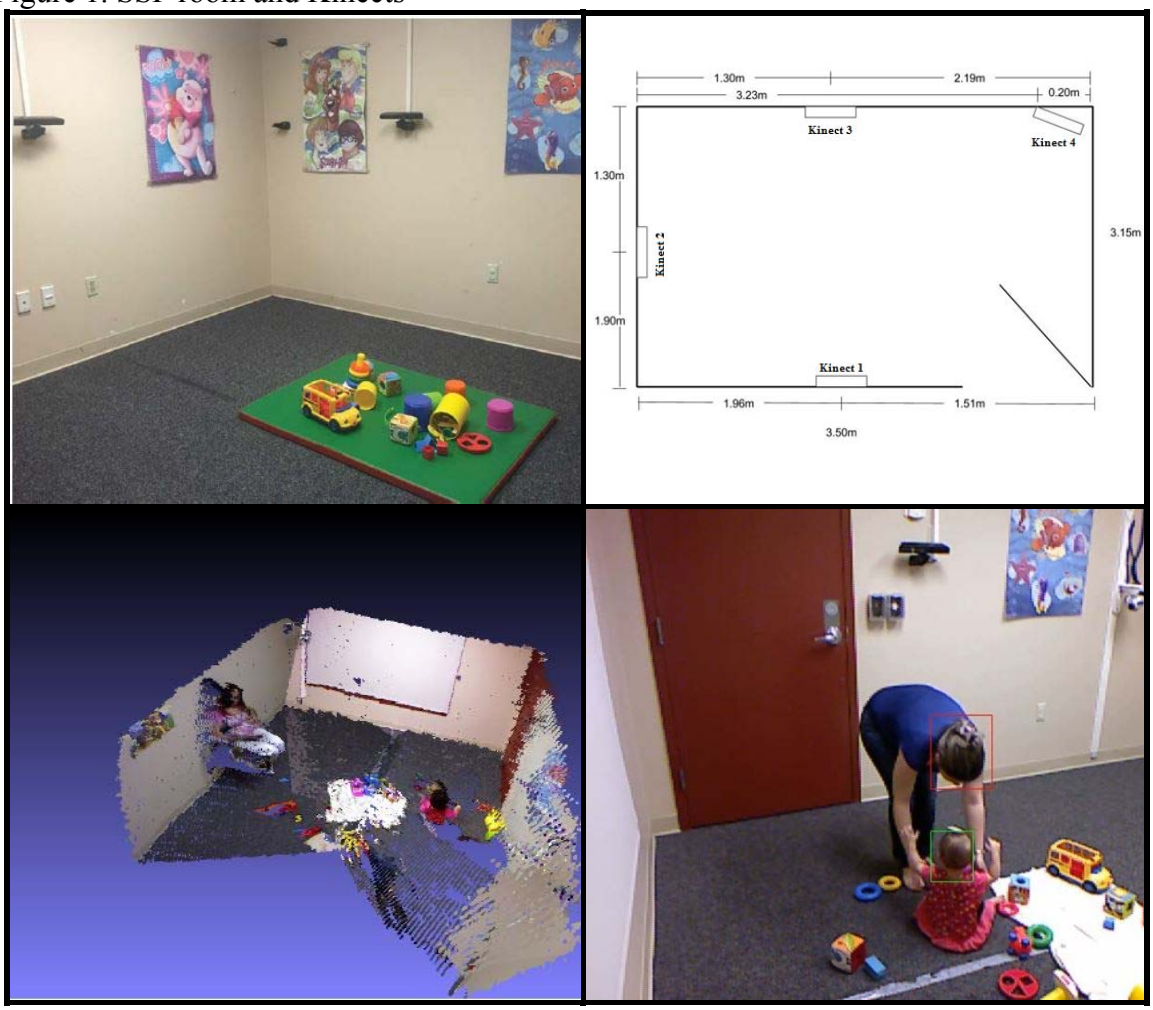
This pilot study included a limited number of infants, highlighting the need for replication with a larger sample size. Tracking captured only the overall position and distance of infant and mother, a significant limitation as infant hand and leg gestures are an important feature of the expert ratings description. This likely impacted not only disorganization scores but also the other expert ratings. For example, in order to receive the highest ratings in proximity-seeking, infants need to gesture to be picked up in addition to approaching the parent (Ainsworth et al., 1978). Highly resistant infants will kick, hit or throw objects and squirm while being held (Ainsworth et al., 1978). While we were able to account for a significant proportion of the variance in expert ratings, the addition of gestural measures may increase the correspondence between objective features and expert ratings. Since data collection occurred, the Kinect 2 has entered the market and may allow for more high definition capture which could address this issue in future work.

This project is a proof-of-principle demonstration that objective measures can be used to predict infant patterns of attachment. We found specific movement and vocal features which were moderately to highly predictive of expert ratings. Dyadic measures (e.g. mean distance and contact duration) were complemented by infant-centered measures (e.g. crying and initial approach) as robust predictors both expert ratings and

dimensional measures of attachment style. Objective measurement of attachment behavior is a promising approach to directly and transparently capturing the complexity of infant and parent behaviors in the SSP.

FIGURES

Figure 1. SSP room and Kinects



Clockwise from top left: (A) Room where the SSP was conducted, two of the four Kinect cameras are visible from this angle. (B) Schematic of the SSP room. Room height = 2.41m; Kinects mounted 1.37m from floor (C) Point-cloud display generated by fusing three Kinect images. Infant and parent are visible in this example (D) Kinect 4 view of parent and infant in the first several seconds of a reunion episode. Bounding boxes (red for parent; green for infant) from the tracker are visible in this video.

Table 1. Associations between expert ratings and dimensional measures of attachment behavior

		Reunion 1				Reunion 2				Overall		
		PS	CM	R	A	PS	CM	R	A	D	A/A	R/D
Reunion 1	PS	1	.71**	.16	-.63**	.32	.42*	.32	-.28	-.08	.83**	.20
	CM		1	.62**	-.65**	.04	.55**	.49**	-.29	-.21	.80**	.44*
	R			1	-.37*	-.12	.29	.45**	-.14	-.13	.37*	.65**
	A				1	-.23	-.52**	-.50**	.37*	.26	-.85**	-.29
Reunion 2	PS					1	.44**	.18	-.55**	.25	.48**	.19
	CM						1	.71**	-.52**	-.03	.77*	.50*
	R							1	-.35*	-.10	.59**	.70**
	A								1	-.21	-.51**	-.38*
Overall	Dis									1	-.12	.43*
	AA										1	.50**
	RD											1

*PS = Proximity-Seeking, CM= Contact-Maintenance, R= Resistance, A= Avoidance, Dis= Disorganized, A/A= Approach/Avoidance Dimension, R/D=Resistance/Disorganized Dimension *p<.05, **p<.01*

Table 2. Objective measures of movement

Measure Name	Calculation Method
Mean Distance	Mean distance (cm) between infant and parent
Contact Initiation	Sum of Yes/No counts of whether infant was moving toward parent in the five seconds before each instance of contact occurred
Contact Duration	Amount of time (seconds) infant was in contact with parent
Time Held	Amount of time (number of tracked frames) infant was carried
Initial Approach	Sum of distance traveled by the infant (m) toward (positive values) or away from the parent (negative values) in the first five seconds of the reunion. This feature assumes negative values if movement away from the mother is greater than movement toward the mother.

Table 3. Descriptive statistics for expert ratings, dimensions, and objective features

		Reunion	Mean	sd	Range
Expert ratings	Proximity-seeking	1	3.41	2.13	1 - 7
		2	4.94	1.48	1-7
	Contact-maintenance	1	2.59	1.76	1-7
		2	4.00	2.02	1-7
	Resistance	1	1.35	.88	1-4
		2	2.38	1.56	1-5
	Avoidance	1	2.68	1.32	1-5
		2	1.85	1.02	1-4
	Disorganized		3.01	1.79	1-7
Dimension	Approach/Avoidance		1.93	1.28	-.17-4.00
	Resistance/Disorganization		.00	.61	-.82-1.33
Objective Features	Mean Distance (cm)	1	1125.49	448.68	379.99-2255.56
		2	944.05	552.75	217.83-2311.69
	Contact initiation	1	1.00	1.23	0-6
		2	1.15	.93	0-3
	Contact duration (seconds)	1	70.77	69.41	.00-227.12
		2	103.13	70.58	.00-192.80
	Time held (frames)	1	235.00	903.37	.00-4681.00
		2	541.18	1228.64	.00-4755.00
	Initial approach (m)	1	.19	.39	-.57-1.26
		2	.31	.47	-.38-1.66
	Crying (reunion) (proportion)	1	.05	.08	.00-.40
		2	.10	.13	.00-.58
	Crying (non-reunion) (proportion)		.11	.14	.00-.45

Table 4. Correlation of expert ratings with objective features

		Expert Ratings					Objective Features						
		Proximity	Contact	Resistance	Avoidance	Disorganization	Mean Distance	Contact Initiation	Contact Duration	Time Held	Initial Approach	Crying (reunion)	Crying (non-reunion)
Expert Ratings	Proximity		.71**	.16	-.63**	-.08	-.61**	.44**	.54**	.09	.58**	.27	.42*
	Contact	.44**		.62**	-.65**	-.21	-.71**	.31	.72**	.46**	.40*	.39*	.51**
	Resistance	.18	.71**		-.37*	-.13	-.48**	.06	.56**	.46**	.01	.65**	.44**
	Avoidance	-.55**	-.52**	-.35*		.26	.55**	-.24	-.57**	-.34*	-.44**	-.32	-.50**
	Disorganization	.25	-.03	-.10	-.21		.07	-.07	-.14	-.22	-.11	.01	.00
Objective Features	Mean distance	-.26	-.78**	-.58**	.39*	.29		-.29	-.87**	-.40*	-.32	-.44**	-.53**
	Contact Initiation	.50**	.08	.11	-.52**	.45**	-.03		.28	.07	.31	-.07	.24
	Contact Duration	.24	.81**	.57**	-.49**	-.20	-.89**	.12		.53**	.26	.45**	.61**
	Time Held	-.02	.40*	.40*	-.25	-.27	-.45**	-.09	.46**		.02	.15	.19
	Initial Approach	.38*	.04	-.16	-.53**	.11	.05	.36*	.05	.10		.06	.36*
	Crying (reunion)	.14	.47**	.63**	-.32	.12	-.35*	.18	.38*	.07	-.21		.74**
	Crying (non-reunion)	.17	.55**	.54**	-.50**	.00	-.56**	.24	.63**	.32	.04	.71**	

Top diagonal is Reunion 1 in blue; Bottom diagonal is Reunion 2 in yellow; Disorganization is a single scale for both reunions

** p< .01; *p<.05

Table 5. Regression prediction of expert ratings using candidate objective features

Expert rating	**Reunion**	**R^2**	**Unique Predictors**	
Proximity-seeking	1	.50	Initial approach	Contact duration
	2	.19	Initial approach	
Contact-maintenance	1	.51	Contact duration	
	2	.66	Contact duration	
Resistance	1	.52	Crying (in reunion)	Contact duration
	2	.53	Crying (in reunion)	Contact duration
Avoidance	1	.42	Initial approach	Contact duration
	2	.50	Initial approach	Contact duration
Disorganization	1 & 2	.20	Contact initiation from the second reunion	
Approach/ Avoidance	1 & 2	.60	Contact duration	Initial approach
Resistance/ Disorganization	1 & 2	.38	Infant crying (in reunion)	

Table 6. Prediction of expert ratings using linear regression with all objective features

Expert Rating	**Reunion**	**R**	**R^2**	**Mean difference between expert and predicted ratings (sd)**
Proximity-seeking	1	.77	.60	1.04 (.85)
	2	.64	.40	.82 (.77)
Contact-maintenance	1	.78	.61	.83 (.71)
	2	.85	.72	.88 (.58)
Resistance	1	.79	.62	.35 (.41)
	2	.78	.60	.80 (.55)
Avoidance	1	.67	.45	.73 (.64)
	2	.80	.64	.48 (.37)
Disorganization	1 & 2	.71	.50	1.0 (.70)
Approach/Avoidance	1 & 2	.84	.71	.50 (.46)
Resistance/Disorganization	1 & 2	.76	.57	.29 (.27)

Note. Predicted ratings were generated using a linear regression of the objective measures (mean distance, infant contact initiation, contact duration, time infant was held, infant initial approach, and infant crying duration during and outside of the reunion) on each expert rating scale. The difference was then taken between the predicted rating and the actual expert rating for each reunion.

Table 7. Tracking by reunion before (A) and after (B) resampling and interpolation

A) Valid Tracking without Resampling			
		Infant	**Parent**
Reunion 1	Missing	39571 (20.8%)	56072 (29.5%)
	Valid	150421 (79.2%)	133920 (70.5%)
Reunion 2	Missing	25906 (14.4%)	41724 (23.1%)
	Valid	154406 (85.6%)	138588 (76.9%)
B) Following Resampling- Interpolation Type			
Reunion 1	Prior to first valid data point	284 (0.2%)	1958 (1.2%)
	Between two valid data points	153622 (92.9%)	158030 (95.6%)
	Following final valid data point	11390 (6.9%)	5308 (3.2%)
Reunion 2	Prior to first valid data	189 (0.1%)	1852 (1.1%)
	Between two valid data points	154499 (97.9%)	140112 (88.8%)
	Following final valid data point	3140 (2%)	15864 (10.1%)

(A) Count of how many frames of each Reunion had valid tracking data for infant and parent (i.e. in Reunion 1, 20.8% of the frames did not have valid tracking data for the infant) (B) 100% of data were interpolated in the resampling process in order to match timings between infant and parent. The method of interpolation is reported here (i.e. 189 frames (0.2% of frames) had data that were interpolated prior to the first valid data point).

Table 8. Rotated component matrix for principal components analysis

		Factor 1 Distance	Factor 2 Crying	Factor 3 Carrying	Factor 4 Infant Approach
Average Distance	Reunion 1	-.70	-	-	-
	Reunion 2	-.83	-	-	-
Contact Duration	Reunion 1	.61	-	-	-
	Reunion 2	.88	-	-	-
Proportion of Time Crying	Reunion 1	-	.91	-	-
	Reunion 2	-	.96	-	-
	Remainder of SSP	-	.73	-	-
Time Held	Reunion 1	-	-	.96	-
	Reunion 2	-	-	.87	_
Contact Initiation	Reunion 1	-	-	-	.69
	Reunion 2	-	-	-	.73
Initial Approach	Reunion 1	-	-	-	-
	Reunion 2	-	-	-	.79

Principal component analysis using varimax rotation revealed a four component structure to the features. Here, only coefficients above the cutoff of |.60| are displayed in order to clearly demonstrate the component structure.

Table 9. Significant correlations between components and expert ratings of attachment behavior

			Expert Attachment Ratings			
		Reunion	Proximity -seeking	Contact-maintenance	Resistance	Avoidance
Components from PCA	Distance	1	.45	.54		-.40
		2		.70	.48	
	Crying	1			.36	
		2			.46	-.37
	Carrying	1		.53	.56	-.36
		2				
	Approach	1	.46			-.52
		2	.38			

Only correlations where p<.05 are shown.

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APPENDIX A.

Occasionally during the SSP, there were frames of the recording without valid tracking, either due to equipment malfunction or occlusion. On average, infants had valid tracking for 79% of Reunion 1 (sd = 0.28) and 86% of Reunion 2 (sd = 0.21). Parents had valid tracking for 71% of Reunion 1 (sd = 0.35) and 78% of Reunion 2 (sd = 0.33) (see Table 7A). Following initial tracking, the data were resampled to create a dataset with standardized time intervals between tracked frames. This allowed for syncing between mother and infant tracking across time. During the resampling process, interpolation was used to estimate the location of the parent and infant when tracking was unavailable. Therefore, after resampling, 100% of frames had a location for the infant and the parent.

There were three types of interpolation. The first type occurred when data were estimated before valid tracking occurred (e.g. the parent enters the room but the first several seconds of her approach are not visible via the tracker). In this case, the individual was assumed to be stationary prior to the first valid data point. The second type of interpolation involved generating data between two valid tracked points, either in the case of resampling between to unevenly timed tracked frames or by filling in missing data (e.g. the infant moves from one side of the room to another and is briefly obscured from view). When resampling between two unevenly timed frames, a simple average was taken between the two frames. When data were missing for a longer period of time, it was assumed that the infant or mother was moving in a straight line from the previously tracked location to the next valid tracked location, and the data were interpolated accordingly. Finally, the third type of interpolation occurred when the data were estimated following the final valid data point (e.g. the infant crawls underneath the

parent's chair and becomes obscured by it for the remainder of the reunion). Just as in the first case, the individual was assumed to remain stationary after tracking ended. The following analysis used data from the first and second type of interpolation, which made up over 90% of the resampled dataset (see Table 7B). Data interpolated prior to the first valid data point were chosen in order to capture the moment when the parent first enters the room during the reunion. In many cases, infants were tracked during those initial moments, but the view of the parent was blocked by the door as it opened. Rather than eliminate the infant data from that time, the interpolation process assumed that the parent was stationary during those first several seconds

APPENDIX B.

In this study, we calculated a set of features based on the 3D movement and audio data gathered from Kinect cameras and LENA recorders. These features: Mean Distance, Holding Time, Contact Time, Contact Initiation, Initial Approach, and Time Crying (in each reunion as well as during the remainder of the SSP) were then used to predict expert ratings of attachment behaviors. Given that expert raters consider multiple behaviors when assigning a rating, it is likely that these features were inter-related, and could be combined into several overarching factors.

Therefore, a principal components analysis of these features was conducted. The PCA included the value of each feature for each reunion as well as the overall proportion of time the child spent crying outside of the reunion episodes. Using a varimax rotation with Kaiser normalization (an orthogonal rotation that does not allow for correlation between factors), the PCA revealed four components with an eigenvalue above one which in total explained 73% of the variance in the features. Features with a correlation coefficient of less than or equal to |.60| were not included in the component.

The four components can be descriptively labelled as Distance (3D distance between the parent and infant in each reunion and time spent in close proximity), Crying (overall proportion of time spent crying throughout the SSP), Carrying (how long the infant was held across both reunions), and Infant Approach (infant contact frequency and movement in the first five seconds of the second reunion) (see Table 8). These four components were moderately correlated with expert ratings of attachment behavior in the SSP (see Table 9) and the dimensional measures of attachment behavior. Distance was

moderately correlated with the Approach/Avoidance dimension ($r=.59$, $p<.01$) and Crying was moderately associated with Resistance/Disorganization ($r=.55$, $p<.01$).