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Continuous measurement of attachment behavior: A multimodal view of the strange situation procedure

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ABSTRACT

Infant attachment is a critical indicator of healthy infant social-emotional functioning, which is typically measured using the gold-standard Strange Situation Procedure (SSP). However, expert-based attachment classifications from the SSP are time-intensive (with respect both to expert training and rating), and do not provide an objective, continuous record of infant behavior. To continuously quantify predictors of key attachment behaviors and dimensions, multimodal movement and audio data were collected during the SSP. Forty-nine 1-year-olds and their mothers participated in the SSP and were tracked in three-dimensional space using five synchronized Kinect sensors; LENA recordings were used to quantify crying duration. Theoretically-informed multimodal measures of attachment-related behavior (e.g., dyadic contact duration, infant velocity of approach toward the mother, and infant crying) were used to predict expert rating scales and dimensional summaries of attachment outcomes. Stepwise regressions identified sets of multimodal objective measures that were significant predictors of eight of nine of the expert ratings of infant attachment behaviors in the SSP's two reunions. These multimodal measures predicted approximately half of the variance in the summary approach/avoidance and resistance/disorganization attachment dimensions. Incorporating all objective measures as predictors regardless of significance levels, predicted individual ratings within an average of one point on the original Likert scales. The results indicate that relatively inexpensive Kinect and LENA sensors can be harnessed to quantify attachment behavior in a key assessment protocol, suggesting the promise of objective measurement to understanding infant-parent interaction.

1. Introduction

Developmental science is starting to adopt objective measurement procedures to capture infant and parent interactive behavior. Objective measurement or behavior imaging has the potential to both reduce the resources required for painstaking expert coding and to increase measurement precision (Dawson & Sapiro, 2019; Edmunds et al., 2017; Messinger, Mahoor, Chow, & Cohn, 2009). Here we apply objective, multimodal measures of attachment behavior to the Strange Situation Procedure (SSP), a gold-standard measure of infant attachment security. Assessment of attachment security during the SSP involves highly-trained raters who generate a gestalt understanding of infant interactive behaviors with the parent. The current proof-of-principle report indicates that an inexpensive set of

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multimodal sensors can be harnessed to reliably measure attachment behaviors during the SSP.

Based on ethological observations and theory, Bowlby (1982) proposed a balance between attachment and exploration motivational systems in the human infant. Infants are motivated to approach and remain close to attachment figures, particularly when distressed. Confidence in an attachment figure's availability indexes attachment security. This confidence facilitates infant's exploration of the environment and is hypothesized to support later social-emotional growth (Bowlby, 1982). Meta-analyses, in fact, indicate strong associations between infant attachment and childhood outcomes (Fearon, Bakermans-Kranenburg, Van IJzendoorn, Lapsley, & Roisman, 2010; Groh et al., 2016). Infants with disorganized and avoidant attachment, for example, are more likely than securely attached infants to exhibit externalizing problems in childhood (Fearon et al., 2010; Groh et al., 2016). By contrast, securely attached infants exhibit higher levels of social competence in childhood than their resistant, avoidant, or disorganized peers (Groh et al., 2016).

The literature on developmental outcomes highlights the importance of assessing early patterns of attachment. However, the field lacks continuous quantitative characterization of the granular behaviors associated with early attachment security. Researchers rely on qualitative descriptions and rating scales to inform attachment classification in the SSP. We asked how effectively inexpensively-gathered continuous measures of multimodal behavior could replicate expert ratings, and whether these multimodal measures provided insight into objective sources of variation that constitute patterns of attachment in the SSP.

1.1. *Attachment and the strange situation procedure*

In the gold-standard SSP, the infant is separated from and reunited with his or her parent twice over the twenty-one-minute procedure (Ainsworth, Blehar, Waters, & Wall, 1978; van IJzendoorn & Kroonenberg, 1990). Trained experts then provide summary ratings of four key infant attachment behaviors during each of the two reunions with the parent. The behaviors are proximity-seeking (approaching parent), contact-maintenance (remaining close to parent), resistance (to contact with parent), and avoidance (ignoring or moving away from parent). Ratings are made on a 7-point Likert scale, which includes behavioral examples that anchor specific ratings (Ainsworth et al., 1978; Waters, 2002).

The premise of the attachment classification process is that the infant's motivation to seek, avoid, or resist the parent during the SSP can be inferred from the infant's behavior during reunions with the parent. Ratings of proximity-seeking index the intensity and persistence of the infant approaching the parent (Waters, 2002). Contact-maintenance indexes the infant's persistent effort to stay in close contact with the parent and unwillingness to end that contact (Waters, 2002). Resistance ratings capture angry/irritable behavior such as pushing away from the parent, kicking or squirming when held, and angry crying (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 ignoring (Waters, 2002). All infants are also assigned a disorganization score on a 1–9 Likert scale which indexes whether infants display a coherent attachment strategy (e.g., approaching the parent when distressed) (Main & Solomon, 1986).

Although the training of expert raters and the classification process itself is resource-intensive, it does not produce a continuous quantitative description of attachment behaviors. Rather, the complexity of both infant and parent behaviors in the SSP are summarized in the 1–7 Likert scales. Objective measurement tools provide a unique opportunity to quantify the role of infant, parent, and dyadic behaviors in predicting expert ratings of proximity-seeking, contact maintenance, resistance, avoidance, and disorganization in the SSP. An important goal, then, is evaluating whether more automated and quantitative patterns of individual and interactive behavior are associated with expert ratings.

Attachment raters use ratings of infant attachment behaviors to assign categorical attachment classifications such as secure, insecure-resistant, insecure-avoidant, and disorganized. Researchers have suggested that attachment status may not be fundamentally categorical (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 applied continuous, granular measures of movement and audio in the SSP to predict approach/avoidance and resistance/disorganization attachment *dimensions*, as well as expert ratings of proximity-seeking, contact-maintenance, resistance, avoidance, and disorganization.

1.2. *Objective measurement and attachment*

To continuously capture infant and parent behavior in the two reunions of the SSP, we used Microsoft Kinect and Language ENvironment Acquisition (LENA) audio recorders and classification software. The Kinect is an inexpensive and widely available sensor that incorporates both a depth sensor and RGB video camera. The depth sensor captures continuous 3D information about the position of individuals in space while the RGB video camera captures texture and color data. The combination of 2D and 3D information allows for modeling of visually represented objects in 3D space (Sivalingam et al., 2012). Kinect has been used to examine motor coordination in face-to-face interaction between infant and mother (Avril et al., 2014), parent-infant contingent responding (Fukuyama et al., 2015; Rehg, 2013), and maternal intrusiveness (Leclère et al., 2016). To our knowledge, however, Kinect-based monitoring of the SSP has not been undertaken.

During the SSP, expert raters attend not only to infants' movements but also their vocalizations. The quantity of crying during both the separation and reunion episodes of the SSP may be a useful indicator of an infant's level of distress and how quickly he or she is comforted by the parent (Ainsworth, 1979). The current study employed LENA recorders to digitize the audio signal during SSP reunions, which was then classified by LENA Gaussian mixture models software to yield a measure of infant non-speech-related vocalizations (e.g., crying, whining, laughing) (Oller et al., 2010; Richards, Gilkerson, Paul, & Xu, 2008). The LENA system has been used to examine parent-child speech across home and school contexts (Perry et al., 2018; Warlaumont, Richards, Gilkerson, & Oller, 2014; Wood, Diehm, & Callender, 2016).

In a previous report, Chow et al. (2018) used objectively measured audio and movement data from 29 of the 49 infants reported here to fit differential equation models with regime-switching models. Chow et al. distinguished proximity seeking and explorations regimes on the basis of both infant and parent movement. Infant vocalizations were associated with a tendency to remain in or transition to proximity-seeking regimes. Chow et al. examined the sample as a whole and did not analyze individual differences in expert ratings, which are the focus of the current investigation.

This study aims to measure the relationship between expert ratings of attachment behaviors and granular measurements of movement and audio recordings. Kinect-based movement tracking and LENA-identified crying were used to generate a multimodal set of behavioral features based on the attachment literature. Attachment theory and its instantiation in SSP ratings focuses almost entirely on infant behavior and intentions (Ainsworth et al., 1978; Waters, 2002). Others, however, have suggested that maternal sensitivity to infant behavior within the SSP may be an unexplored source of variance in infant attachment ratings (Behrens, Parker, & Haltigan, 2011). Specifically, maternal sensitivity ratings were associated with expert ratings of infant proximity-seeking, contact maintenance, and avoidance (though not resistance) during the SSP. While Behrens et al. (2011) suggests that maternal SSP behavior is associated with expert ratings of infant attachment behaviors, the nature of this association is not clear. The current study integrates continuous measures of mother movement to better understand the role of maternal behavior (as well as infant behavior and dyadic interaction) in

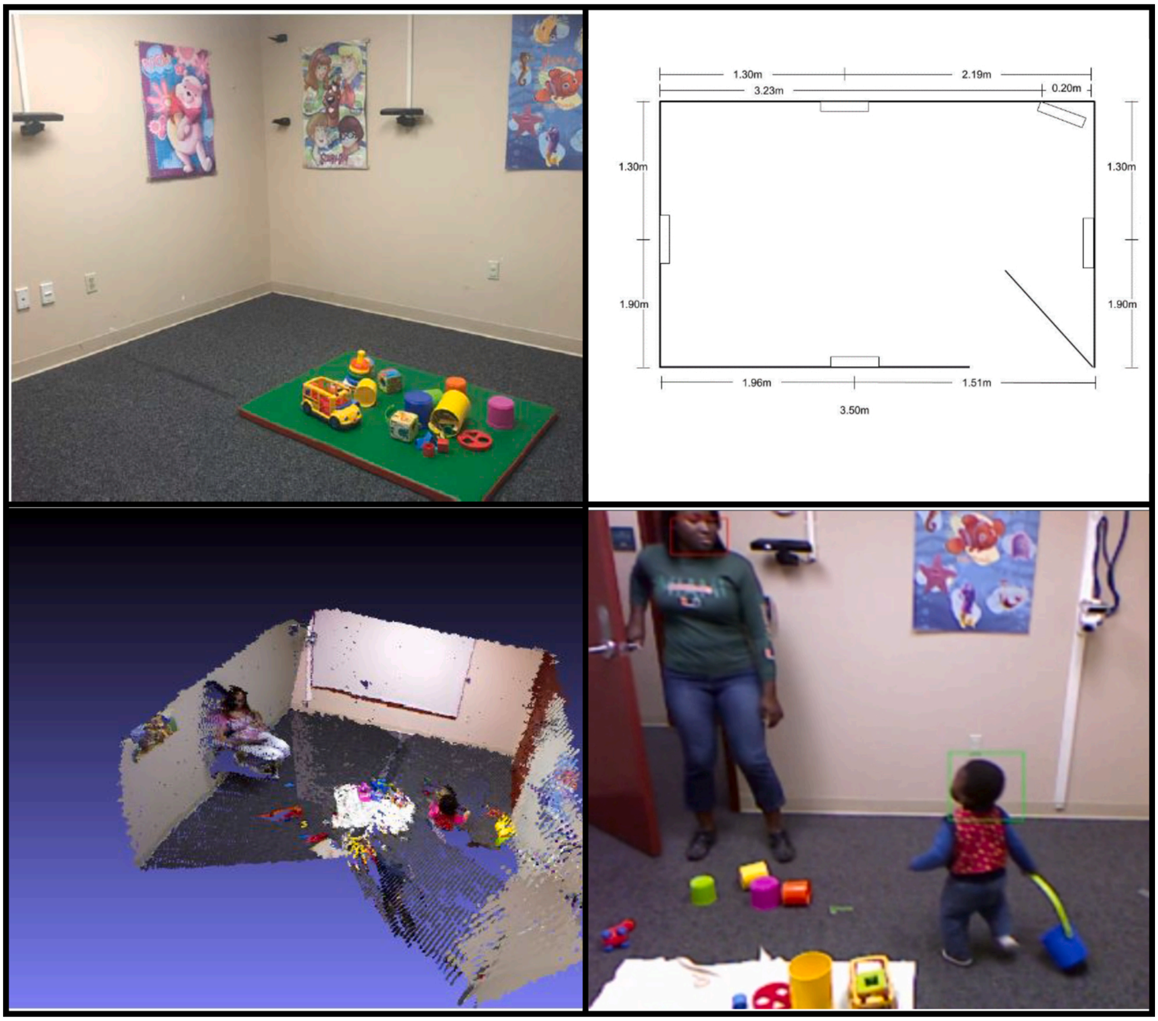

Fig. 1. Clockwise from top left: (A) Room where the SSP was conducted, two of the five Kinect cameras are visible from this angle. (B) Schematic of the SSP room. Room height = 2.41 m; Kinects mounted 1.37 m from floor; Kinects are represented by rectangles along walls (C) Point-cloud display generated by fusing three Kinect images. Infant and parent are visible in this example (D) Kinect RGB 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 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

influencing expert attachment ratings.

1.3. Current study

In the current study, we categorized behavioral features as dyadic (e.g., contact time between parent and infant), infant-focused (e.g., infant approaching the parent), or mother-focused (e.g., mother approaching the infant). We used stepwise regression models to examine multivariate associations between those objective behavioral features and the expert ratings and dimensional scales of attachment. Finally, we employed a bottom-up data driven approach in multivariate regression models in which all objective features were employed to predict expert ratings and dimensional measures. This approach seeks to ascertain how closely the objective measures replicate expert ratings and dimensional measures of attachment.

2. Method

2.1. Participants

Forty-nine mother-infant dyads (30 male infants) completed the SSP around the infants' first birthday (*M* age = 12.11 months, sd = 0.57). Ethnically, 71 % of the sample identified as Hispanic or Latino. Racially, the sample identified as 82 % Caucasian, 16 % Black, and 4% Asian. A community sample was recruited through Miami-Dade County birth records, word of mouth, flyers, social media, and attendance at community events for expectant and new parents. Selection criteria excluded low birthweight and premature infants, as well as infants with sensory and motor impairments or identified metabolic, genetic, or progressive neurological disorders.

2.2. Protocol

The SSP 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 s of crying; Waters, 2002), which occurred in 45 % of cases. Episodes 5 and 8, referred to as Reunion 1 and Reunion 2, are the focus of experts' rating of attachment behaviors and the focus of this study (Ainsworth et al., 1978; Waters, 2002). The SSP was conducted in a playroom (3.15m × 3.45m x 2.4 m) equipped with five Microsoft Kinect sensors and 2 Elmo PTC-400C PTZ Cameras which recorded to DVD in an associated control room (see Fig. 1). Expert raters used the DVD recordings for behavioral ratings of the SSP.

2.3. Measures

2.3.1. 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). Proximity-seeking focuses on the infant's behavior when the mother returns to the room; coders consider how quickly infants approach the mother, infant vocalizations as bids for attention, and infant gestures such as lifting the arms to be held (Ainsworth et al., 1978). Contact-maintenance focuses on the extent to which the infant clings to or attempts to stay close to the parent after achieving contact; coders consider the duration of time the infant is held and how many instances in which the child actively attempts to maintain contact with the mother by clinging or reaching (Ainsworth et al., 1978). Resistance focuses on the infant's expression of anger at the mother; coders consider infant crying and aggression throughout the reunion (Ainsworth et al., 1978). Avoidance focuses on how the infant moves away from or ignores the mother upon her return at the start of the reunions; coders consider the orientation of the infant, vocalizations, and movement toward or away from the mother (Ainsworth et al., 1978). Raters consider the two reunions separately because changes in infant behavior over the entirety of the SSP are used to understand overall attachment classification (Ainsworth et al., 1978).

The expert rater also rated the infant's level of disorganized 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, which is linked to contradictory behavior patterns, stereotypies, freezing, and/or overt displays of fear toward the parent (Main & Solomon, 1986).

2.3.2. Dimensions of attachment behavior

To generate continuous measures of attachment behaviors, we combined the five rating scales into the approach/avoidance and resistance/disorganization dimensions (Fraley & Spieker, 2003). Approach/avoidance was calculated by taking the mean of proximity-seeking, contact-maintenance, and the inverse of avoidance scores. Higher scores, then, indicate greater approach and contact maintenance but lower avoidance. Resistance/disorganization was calculated by standardizing resistance and disorganization ratings using Z-scores and taking their mean so that higher scores indicate greater resistance and disorganization. Z-scores accounted for the differences in the Likert scales for resistance (1–7) and disorganization (1–9) (Fraley & Spieker, 2003). Associations between and among 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.

2.3.3. Reliability

Although not a focus of project analyses, the expert rater classified the 49 infants in the study as insecure-avoidant (n = 2), insecure-resistant (n = 8), secure (n = 29), and disorganized (n = 10). For a subset of the infants (n = 24), a second Minnesota-trained and reliable rater completed independent ratings and classifications. There was 100 % agreement between raters for the A, B, and C security classifications and 98 % agreement on disorganization classification. Analyses focused on predicting expert attachment ratings. Absolute individual two-way mixed intraclass correlations (ICC) were employed (see Appendix for weighted Cohen's Kappa). The ICCs indicate the proportion of rating variance attributable to differences in the object of measurement (episodes). They indicated high reliability for proximity-seeking (Reunion 1 *ICC* = .91; Reunion 2 *ICC* = .86), contact-maintenance (Reunion 1 *ICC* = .94; Reunion 2 *ICC* = .91), resistance (Reunion 1 *ICC* = .92; Reunion 2 *ICC* = .89), and avoidance (Reunion 1 *ICC* = .83; Reunion 2 *ICC* = .84), but lower reliability for disorganization (*ICC* = .45). Lower reliability on disorganization scores is not uncommon (e.g., Turton, Hughes, Fonagy, & Fainman, 2004).

2.3.4. Movement tracking

Kinect RGB videos were recorded with a spatial resolution of 640 × 480 pixels and a temporal resolution of approximately 30 frames-per-second. The Kinect sensor controls for 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). In post processing, we fused Kinect video and depth recordings, projecting up to four of the five Kinect measurements into a single 3D map to enhance localization accuracy (see Fig. 1). This was accomplished by finding common point correspondences between images, and computing 3D rigid transformation, using the Singular Value Decomposition method (Ciptadi, 2016).

Mother's and infant's heads were tracked in 3D space during the two reunions using a user-in-the-loop system (Ciptadi, 2016). For this user-in-the-loop system, human trackers viewed 2D camera images captured by the RBG camera and indicated the top left and bottom right points of a bounding box that was then automatically drawn around the head, differentiating it from its surround. Adopting a computer vision approach, we then estimated a 3D template of the head's location. The location of the head-containing bounding box was tracked over successive frames based on similarities in the distributions (histograms) of grey scale and color values. A linear Kalman filter adjusted predicted locations based on the bounding box's previous location and trajectory (Ciptadi, 2016). The human tracker noted when the bounding box no longer contained at least 60 % of the head (e.g., if the infant's head was occluded or could not be detected) and corrected tracking (see Appendix). Infant and mother were each tracked in each of the two 3-minute reunions. A mean of 7 user corrections were required per minute of video tracked, yielding 42 corrections per SSP.

In approximately 80 % of SSPs, the first or second author tracked infant and mother head positions; trained research assistants tracked the remainder. By way of training, research assistants observed a tracking and then tracked a participant under the first author's direct supervision. The first author reviewed all research assistant tracking; we did not assess the reliability of human trackers with one another.

We synchronized tracking for infant and mother to assure a common timestamp by resampling the respective data streams from the raw Kinect rate of approximately 30 frames per second to a common 25 frames per second, a .04 s interval. When infant and mother were out of view of the camera, we estimated their position based on where they had last been tracked and where they were next seen. The mean percentage of tracked frames was 88 % (sd = 17 %) for infants and 82 % (sd = 26 %) for mothers. We used interpolation to estimate the location of the parent and infant when tracking was unavailable (e.g., the infant was briefly obscured from view as s/he moved) with the assumption that the infant or mother moved in a straight line at constant velocity from the previously tracked location to the next tracked location. We made this assumption based on the pattern of occlusions that occurred in tracking. Specifically, infants were most frequently occluded when they sat in a specific corner of the room. Mothers were most frequently occluded when they sat in their chair and video capture error occurred. In both cases, the movement of the infants and mothers was limited during the time they were not visible to the trackers. The vast majority of interpolated segments were 3 frames or less in length, 97.7 % for the mother and

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	.69**	.24	−.66**	.38**	.45**	.24	−.33*	−.08	.82**	.19
	CM		1	.67**	−.67**	.05	.58**	.42**	−.42**	−.04	.80**	.49**
	R			1	−.42**	−.12	.29*	.51**	−.32	.15	.41*	.78**
	A				1	−.23	−.48**	−.39**	.42**	.16	−.78**	−.30*
Reunion 2	PS					1	.36**	.05	−.46**	.09	.54**	.01
	CM						1	.55**	−.55**	.00	.79**	.40**
	R							1	−.40*	.10	.46**	.76**
	A								1	−.17	−.67**	−.42**
Overall	Dis									1	−.02	.59**
	A/A										1	.40**
	R/D											1

Notes. 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.

98.0 % for the child (see Appendix). In addition, at the beginning of each reunion, if either infant or mother was not visible to the Kinect-based tracker, we assumed that individual to be stationary. In total, 11 % of infant frames and 15 % of mother frames were interpolated. Untracked frames that were not interpolated (e.g., at the end of an episode) constituted missing data (1% of frames for infants and 3% of frames for mother).

Following tracking, we used infant and mother head position in 3D space to continuously calculate the location of each partner, the distance between the two partners, and the velocity of each partner's movement. All distance measures are reported in meters. We calculated velocity using the .04 second frame interval and is reported as meters per second. Infant velocity values indexed the infant's movement toward or away from the mother's position in the previous .04 s interval (Mohan et al., 2018).

We used location in the room, distance between mother and child, and velocity metrics to create theoretically-informed measures of attachment behavior (see Table 2). These features included infant-focused, mother-focused, and dyad-focused behavior patterns that had expected associations with expert ratings of attachment behavior. Dyadic features included contact duration, the number of seconds the infant and mother were within .8 m of one another, and time held, the number of seconds the infant was carried by the mother. Carrying was defined as periods when the infant was more than .9 m above the floor. (See the Appendix for sensitivity analyses of these .8 and .9 m thresholds). Infant-focused variables included infant contact initiation, a count of how frequently the infant initiated contact with the mother (within .8 m) throughout the reunion, and infant initial approach, the sum of distance traveled by the infant (m) toward (positive values) and away from the mother (negative values) in the first five seconds of the reunion (Ainsworth, et al., 1978). Infant velocity *throughout each reunion* was also segregated into positive and negative values. Mean values of positive velocity (infant velocity toward the mother) and negative velocity (infant velocity away from the mother) were calculated. Mother-focused variables—mother initial approach, mother velocity toward the infant and velocity away from the infant—paralleled infant variables (see Table 2).

2.3.5. Audio analysis

Language ENvironment Analysis (LENA) recorders captured audio from all infants. The resulting audio files were analyzed using LENA Gaussian mixture models, which distinguish child speech and non-speech vocalizations (Oller et al., 2010). The majority of infants ($n = 39$) were outfitted with LENA recorders during the SSP which were carried in a specially designed vest worn by the infant. For the additional dyads ($n = 10$), LENA data was captured from the audio track of SSP audiovisual recordings via a ceiling microphone at a rate of 44.1 kHz. See the Appendix for a comparison of these audio sources. As the SSP is designed to activate the attachment system, it was assumed the majority of the audio coded as infant non-speech vocalizations originated from crying, rather than laughter or other vegetative sounds. To test that assumption, we conducted manual coding of the two reunions from 29 randomly chosen SSPs. 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 $ICC = .87$ and Reunion 2 $ICC = .94$). The proportion of time spent crying relative to the total duration of each reunion was the final infant objective feature used to predict expert ratings.

3. Results

Associations among objective multimodal behavioral features within and between reunions are contained in Tables 3a and 3b. The Appendix contains a factor analysis of these features. A statistical description of all variables is contained in Table 4. Correlations indexing univariate associations between objective features and expert ratings and dimensional measures are presented in Table 5. In the project's multivariate analyses, stepwise linear regression models identified sets of objective features that uniquely and significantly predicted expert ratings and dimensional measures. Finally, a comprehensive regression approach, which included all multimodal features as predictors, determined how closely objective measures replicated expert ratings and dimensional measures using all

Table 2
Multimodal Objective Measures.

Measure Name	Type	Calculation Method
Contact Duration	Dyadic	Number of seconds infant and mother were in contact.
Time Held	Dyadic	Number of seconds the infant was carried by the mother.
Contact Initiation	Infant	Sum of instances in which the infant moved toward the mother (positive velocity over 5 s) and established contact.
Infant Initial Approach	Infant	Sum of distance traveled by infant (m) toward (positive values) or away from mother (negative values) in the first five seconds of the reunion.
Infant Velocity Toward	Infant	Mean of positive velocity values (indexing infant movement toward mother) over the course of the reunion.
Infant Velocity Away	Infant	Mean of negative velocity values (indexing infant movement away from mother) over the course of the reunion.
Crying	Infant	The summed duration of infant non-speech vocalizations divided by the total duration of the reunion episode
Mother Initial Approach	Mother	Sum of distance traveled by mother (m) toward (positive values) or away from infant (negative values) in the first five seconds of the reunion.
Mother Velocity Toward	Mother	Mean of positive velocity values (indexing mother movement toward infant) over the course of the reunion.
Mother Velocity Away	Mother	Mean of negative velocity values (indexing mother movement away from infant) over the course of the reunion.

Notes. Contact occurred when the infant's head was within 80 cm (approximately arm's length) of the mother's head. Time held indicated that the infant's head was more than 90 cm away from the floor.

Table 3a
Correlation of pairwise objective features within each reunion.

		Reunion 1									
		Contact Duration	Time Held	Contact Initiation	Infant Initial Approach	Infant Velocity Toward	Infant Velocity Away	Crying	Mother Initial Approach	Mother Velocity Toward	Mother Velocity Away
Reunion 2	Contact Duration		.50**	.37**	.13	−.05	.06	.33*	.15	.38**	−.10
	Time Held	.46**		−.04	−.04	.02	−.07	.15	.15	.13	−.05
	Contact Initiation	.04	−.19		.11	.12	−.04	.06	.13	.33*	−.02
	Infant Initial Approach	.02	−.22	−.01		.01	.13	.06	−.27	.06	−.22
	Infant Velocity Toward	.04	.14	.19	.09		−.86**	−.14	.04	.08	.01
	Infant Velocity Away	−.01	−.06	−.27	−.01	−.91**		.14	−.02	−.02	−.05
	Crying	.32*	.01	.15	.04	−.08	.07		.30*	.23	−.05
	Mother Initial Approach	.12	.09	−.00	.05	−.14	.21	.32*		.18	−.18
	Mother Velocity Toward	−.06	.02	.05	.01	.15	−.07	.04	.24		.09
	Mother Velocity Away	.02	−.08	.01	.02	−.13	.08	.10	−.06	−.76**	

Notes. Correlations of variables within Reunion 1 are in the upper triangle and correlations of variables within Reunion 2 are in lower triangle. *$p < .05$, **$p < .01$.

Table 3b
Correlation of objective features between reunions.

		Reunion 1									
		Contact Duration	Time Held	Contact Initiation	Infant Initial Approach	Infant Velocity Toward	Infant Velocity Away	Crying	Mother Initial Approach	Mother Velocity Toward	Mother Velocity Away
Reunion 2	Contact Duration	.50**	.28	.31*	.15	.08	.02	.33*	.03	.12	.05
	Time Held	.42**	.69**	−.02	.07	−.02	.01	.17	.09	.08	−.01
	Contact Initiation	−.14	−.13	.12	.08	.14	−.17	−.14	.03	−.09	.17
	Infant Initial Approach	.06	−.23	.09	.36*	.06	.02	−.01	−.20	−.20	−.03
	Infant Velocity Toward	−.11	−.05	.03	.19	.66**	−.60**	−.15	.09	.01	−.11
	Infant Velocity Away	.09	.02	−.08	−.20	−.60**	.62**	.12	−.10	−.01	.21
	Crying	.03	.01	.13	.27	−.08	.11	.76**	.18	.06	.05
	Mother Initial Approach	−.02	.07	.08	.09	.06	−.06	.22	.34*	.00	−.01
	Mother Velocity Toward	.13	−.05	.09	.21	−.11	.19	−.07	.14	.26	−.20
	Mother Velocity Away	−.12	.00	.01	−.19	.22	−.28	.18	−.08	−.13	.43**

Notes. *p < .05, **p < .01.

Table 4
Descriptions of expert ratings, attachment dimensions, and objective features.

		Reunion	Mean	sd	Range
Expert ratings	Proximity-seeking	1	3.7	2.0	1–7
		2	5.1	1.6	1–7
	Contact-maintenance	1	2.9	1.8	1–7
		2	4.1	1.9	1–7
	Resistance	1	1.7	1.3	1–6
		2	2.6	1.6	1–5
	Avoidance	1	2.6	1.3	1–5
		2	1.8	1.0	1–5
Dimensions	Disorganized		3.0	1.8	1–7
	Approach/Avoidance		2.2	1.2	0–4.3
	Resistance/Disorganized		0	.7	−.9 – 2.1
Objective Features	Contact duration (seconds)	1	69.6	68.7	0–227.1
		2	103.2	66.4	0–192.8
	Time held (seconds)	1	8.2	30.8	0–187.2
		2	20.4	43.9	0–172.8
	Contact Initiation	1	4.8	4.3	0–20
		2	4.4	4.4	0–16
	Infant initial approach (m/s)	1	.0	.1	−.1–.2
		2	.0	.1	−.2–.3
	Infant Velocity Toward (m/s)	1	.1	0.0	0–.2
		2	.1	0.0	0–.2
	Infant Velocity Away (m/s)	1	−.1	0.0	−.2–0
		2	−.1	0.0	−.2–0
	Crying	1	.1	.1	0–.4
		2	.1	.1	0–.6
	Mother initial approach (m/s)	1	.2	.1	−.3–.5
		2	.2	.2	−.2–.6
	Mother Velocity Toward (m/s)	1	.1	0.0	0–.2
		2	.1	0.0	0–.2
	Mother Velocity Away (m/s)	1	−.1	.1	−.2–0
		2	−.1	0.0	−.2–0

Table 5
Correlation of expert ratings with objective features.

		Expert Ratings, Reunion 1				
		Proximity	Contact	Resistance	Avoidance	Disorganization
Objective Features, Reunion 1	Contact Duration	.50**	.74**	.51**	−.59**	−0.08
	Time Held	.05	.40**	.33*	−.28*	−0.16
	Contact Initiation	.37**	.23	.02	−.32*	−.08
	Infant Initial Approach	.37**	.26	−.18	−.33*	.05
	Infant Velocity Toward	.18	.13	.04	−.07	.34*
	Infant Velocity Away	−.05	−.07	−.02	−.08	−.37**
	Crying	.25	.40**	.62**	−.33*	.14
	Mother Initial Approach	.13	.17	.27	−.32*	.11
	Mother Velocity Toward	.20	.22	.25	−.11	.13
	Mother Velocity Away	−.42**	−.28	−.14	.39**	−.15
		Expert Ratings, Reunion 2				
		Proximity	Contact	Resistance	Avoidance	Disorganization
Objective Features, Reunion 2	Contact Duration	.19	.83**	.50**	−.54**	−.14
	Time Held	.01	.44**	.24	−.20	−.20
	Contact Initiation	.02	−.01	.07	−.22	.26
	Infant Initial Approach	.25	.16	−.10	−.39**	.02
	Infant Velocity Toward	.15	.21	.04	−.33*	.30*
	Infant Velocity Away	−.12	−.18	−.10	.26	−.32*
	Crying	.10	.34*	.64**	−.36*	.18
	Mother Initial Approach	.20	.28	.25	−.19	.07
	Mother Velocity Toward	.24	.01	.00	−.18	.12
	Mother Velocity Away	−.24	.02	.05	.08	.06

Notes. Disorganization ratings pertain to both reunions. *$p < .05$, **$p < .01$.

available information.

3.1. 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 5). Stepwise linear regression models indicated the combination of unique features in each reunion which best predicted the variance in expert ratings of proximity-seeking, contact-maintenance, resistance, avoidance, and disorganization, as well as the variance in the approach/avoidance and resistance/disorganization dimensions. In the stepwise results, each objective feature is a unique, significant predictor of expert ratings in a given reunion (see Table 6). In the prediction of disorganization ratings and the approach/avoidance and resistance/disorganization dimensions, the mean values of objective features across the two reunions were used as predictors.

3.1.1. Proximity-seeking ratings

In reunion 1, dyadic contact duration, mother velocity away from the infant, time held, and infant velocity toward the mother were unique significant predictors of proximity-seeking, *Adj.* $R^2 = .45$. Higher proximity-seeking ratings were associated with longer periods of dyadic contact, lower velocity of mother movement away from the infant, less time in which the infant was held by the mother, and a higher velocity of infant movement toward the mother. In reunion 2, no objective features emerged as significant predictors of proximity-seeking.

3.1.2. Contact-maintenance ratings

In reunion 1, contact duration and mother velocity away from the infant uniquely and significantly predicted contact-maintenance ratings, *Adj.* $R^2 = .57$. In reunion 2, dyadic contact duration, mother initial approach, and infant velocity away from the mother uniquely and significantly predicted contact-maintenance, *Adj.* $R^2 = .75$. In both reunions, infants with higher contact-maintenance ratings spent more time in close contact with their mothers. In reunion 1, higher contact maintenance ratings were associated with lower velocity of mother movement away from the infant. In reunion 2, higher ratings were associated with higher velocity of mother movement toward the infant and lower velocity of infant movement away from the mother.

3.1.3. Resistance ratings

In reunion 1, the proportion of infant crying, dyadic contact duration, and infant initial approach were unique, significant

Table 6
Stepwise regression results.

	RE	R^2	*F(df)*	Predictor Variables	Predictor Statistics		
					B	*t*	*p*
Proximity Seeking	1	.49	10.74 (4, 44)	Contact Duration	.61	4.96	<.001
				Mother Velocity Away	−.38	−3.51	.001
				Time Held	−.28	−2.29	.027
				Infant Velocity Toward	.22	2.04	.048
	2	No significant predictors					
Contact Maintenance	1	.58	32.27 (2, 46)	Contact Duration	.72	7.48	<.001
				Mother Velocity Away	−.21	−2.20	.033
	2	.76	47.96 (3, 45)	Contact Duration	.80	10.99	<.001
				Mother Initial Approach	.24	3.19	.003
				Infant Velocity Away	−.23	−3.10	.003
Resistance	1	.55	18.46 (3, 45)	Crying	.51	4.82	<.001
				Contact Duration	.37	3.49	.001
				Infant Initial Approach	−.26	−2.62	.012
	2	.51	24.21 (2, 46)	Crying	.54	4.96	<.001
				Contact Duration	.33	3.07	.004
Avoidance	1	.49	18.70 (2, 46)	Contact Duration	−.55	−5.00	<.001
				Mother Velocity Away	.33	−3.01	.004
	2	.55	13.41 (4, 44)	Contact Duration	−.45	−4.18	<.001
				Infant Initial Approach	−.34	−3.34	.002
				Infant Velocity Toward	−.30	−2.94	.005
				Crying	−.22	−2.09	.043
Disorganization	1 & 2	.14	7.53 (1, 47)	Infant Velocity Away	−.37	−2.74	.009
Approach/ Avoidance	1 & 2	.71	21.13 (5, 43)	Contact Duration	.65	7.81	<.001
				Infant Initial Approach	.26	3.05	.004
				Mother Velocity Away	−.19	−2.23	.031
				Infant Velocity Toward	.21	2.55	.014
				Mother Initial Approach	.19	2.25	.030
Resistance/ Disorganization	1 & 2	.43	25.46 (2, 46)	Crying	.63	5.63	<.001
				Infant Velocity Away	−.29	−2.56	.014

Note. All *F* statistics are significant at $p < .05$.

predictors of resistance, *Adj.* $R^2 = .52$. In reunion 2, crying proportion and dyadic contact duration were unique, significant predictors of resistance, *Adj.* $R^2 = .49$. Infants with higher resistance ratings cried for a longer portion of the reunions and spent more time in close contact with the mother across both reunions. During the initial five seconds of reunion 1, infants who scored higher in resistance exhibited lower velocity of movement toward the mother.

3.1.4. Avoidance ratings

In reunion 1, dyadic contact duration and mother velocity away from the infant were unique, significant predictors of avoidance ratings, *Adj.* $R^2 = .42$. In reunion 2, contact duration, infant initial approach, infant overall velocity toward the mother, and infant crying were unique, significant predictors of avoidance, *Adj.* $R^2 = .51$. Higher avoidance ratings were associated with lower time in dyadic contact in both reunions. In reunion 1, higher ratings were also associated with increased maternal velocity away from the infant. In reunion 2, higher avoidance ratings were associated with lower infant velocity toward the mother both in the initial five seconds and overall, and lower levels of infant crying.

3.1.5. Disorganization

Velocity away from the mother was a unique, significant predictor of disorganization ratings, *Adj.* $R^2 = .12$. Infants with higher disorganization ratings exhibited a higher velocity of movement from their mothers than other infants.

3.1.6. Dimensional measures

Dyadic contact duration, infant initial approach, and mother velocity away from the infant, infant velocity toward the mother, and mother initial approach were unique, significant predictors of the approach/avoidance attachment dimension, *Adj.* $R^2 = .68$). Infants higher on the approach/avoidance dimension were in dyadic contact with mother for longer and approached mother with a higher velocity upon her return and throughout the reunions than lower-scoring infants. In addition, higher scores on the approach/avoidance dimension were associated with lower velocity of mother movement away from the infant across the reunions and higher velocity of movement toward the infant at the outset of the reunions. Infant crying and velocity away from the mother were unique, significant predictors of the resistance/disorganization attachment dimension, *Adj.* $R^2 = .41$. Infants higher on the resistance/disorganization dimension cried more during both reunions and demonstrated higher velocity away from the mother than lower-scoring infants.

3.2. Comprehensive regression approach

A bottom-up approach to the prediction of expert ratings involved combining all objective features into a comprehensive regression equation. This approach indicates how closely continuous multimodal measures can replicate summary ratings, and the proportion of variance in ratings captured by the continuous measures of behavior. This 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 comprehensive linear regression, all objective features were combined to predict expert ratings in each reunion, as well as disorganization ratings, and the attachment dimensions. The mean R^2 value for predicting expert ratings from the ensemble of objective features was .56 (sd = .18, range .21 to .80). When the unstandardized predicted values from these comprehensive regression equations were compared to the actual expert ratings, the difference was, on average, less than one Likert point on the original 7-point rating scale (mean difference = .78; sd = .22 range = .50–1.13) (see Table 7). The mean difference on the 9-point disorganization scale was 1.24 (sd = .97) points. Finally, dimensional attachment measures were both well predicted by the combination of all objective features (approach/avoidance $R^2 = .73$; resistance/disorganization $R^2 = .52$).

4. Discussion

Attachment theory is grounded in the careful, manual description of infant-parent interaction (Ainsworth et al., 1978; Bowlby, 1982). In the Strange Situation Procedure, attachment is conceptualized as a set of interdependent infant behaviors that signal infant

Table 7
Comprehensive regression results.

Expert rating	Reunion	R^2	*F*	*p*	Mean Difference from Expert Ratings (standard deviation)
Proximity-seeking	1	.56	4.84	<.00	1.01 (.85)
	2	.21	.98	.47	1.13 (.81)
Contact-maintenance	1	.67	7.74	<.00	.83 (.64)
	2	.80	15.62	<.00	.69 (.50)
Resistance	1	.62	6.25	<.00	.60 (.53)
	2	.57	5,10	<.00	.85(.65)
Avoidance	1	.64	6.62	<.00	.61 (.47)
	2	.60	5.62	<.00	.50 (.42)
Disorganization	1 &2	.27	1.37	.23	1.24 (.97)
Approach/Avoidance	1 & 2	.73	10.23	<.00	.49 (.38)
Resistance/Disorganization	1 & 2	.52	4.15	<.00	.36 (.33)

goals. Attachment behavior rating scales facilitate highly trained expert interpretation of these infant behaviors. The current results indicate that continuous, objective measurements can accurately capture a high proportion of variance in these rated attachment behaviors and in the attachment dimensions that summarize patterns of attachment in the SSP.

This is the first application of multimodal objective measurement to the prediction of attachment behaviors in the SSP of which we are aware. Stepwise regression equations indicated that objective measures were significant predictors of eight of nine of the expert ratings of infant attachment behaviors in the two SSP reunions. With all objective measures used as predictors in comprehensive regression models, individual ratings were, on average, predicted to within one point on the original Likert scales. Both the Kinect (approximately $150) and LENA recorders (approximately $400) are relatively inexpensive, and the regression models employed to predict attachment behaviors are straightforward. Thus, the current paper suggests a relatively accessible potential approach to objectively measuring complex interactive behavior.

4.1. Correspondences between expert ratings and objective features

4.1.1. Proximity-seeking

Proximity-seeking behavior in the first reunion was well captured by objective measures of close dyadic contact and time held, the velocity of the infant's movement toward the mother, and the velocity of the mother away from the infant. Infants who spent more time in close contact with their mothers but were held for less time were rated higher in proximity seeking. Likewise, infants who moved toward their mothers more quickly and infants whose mothers moved away from them more slowly were rated higher in proximity seeking.

Expert rating scales indicate that infants high in proximity-seeking "purposefully approach the adult" and maintain contact with the parent for over 15 s (Ainsworth et al., 1978, pp. 343–344). Thus, objective measures of the first reunion highlight the role of the dyadic measure of contact duration and the infant-centered approach measure in indexing proximity-seeking. Within the context of close dyadic contact, longer times being held by the parent may have constrained infant's ability to approach the parent.

In the SSP, parents are instructed to return to their chairs when they are ready to do so after greeting and settling their infants (Ainsworth et al., 1978). The speed with which mothers moved away from their infants in such circumstances was associated with the infant's proximity seeking ratings. This is noteworthy as parental movement away from the child is not described as contributing to proximity seeking ratings (Ainsworth et al., 1978; Waters, 2002). As discussed below, this finding suggests that dyadic interaction between infant and mother is associated with ratings of infant behavior.

In the second reunion, no objective features significantly predicted proximity seeking. It is possible that infants' approach to the door through which the mother would enter *prior* to the reunion (not captured by the Kinect-based tracking) informed expert ratings of proximity-seeking. In addition, proximity-seeking ratings also consider the infant's use of gestures (e.g., raising arms for "up"), a feature not captured by the current measurement approach, which could inform proximity-seeking scores in both reunions.

4.1.2. Contact-maintenance

Contact-maintenance in both reunions was well captured by granular measures of close dyadic contact. In dyads with higher time in contact, infants received higher contact-maintenance ratings. The expert contact-maintenance ratings instructions rely heavily on duration, and explicit cut-offs are articulated for specific ratings (Ainsworth et al., 1978). Slower mother movement away from the infant in the first reunion and quicker movement toward the infant in the second reunion also contributed to higher infant contact-maintenance ratings. However, mother movements are not mentioned in contact-maintenance rating instructions. Raters are instructed to consider infant clinging to the parent (Ainsworth et al., 1978). Although not directly captured by the current approach, such clinging could have contributed to the finding that higher contact-maintenance was associated with slower infant movement away from the mother in the second reunion.

4.1.3. Resistance

Resistance was well predicted by objectively measured infant crying and time in close dyadic contact. Rating guidelines indicate that infants high in resistance may be held by the mother for an extended period without being soothed (Waters, 2002). High levels of resistance are conceptualized as indexing an infant's anger toward the parent. Arguably, a pattern of vocal distress despite long periods of contact may capture the anger thought to characterize high levels of resistance. Alternately, the anger thought to motivate resistance is, more simply, an inability to soothe when in contact with the parent.

4.1.4. Avoidance

High levels of avoidance were well captured by low levels of close dyadic contact in both reunions. In the first reunion, these features were complemented by quicker movement of the mother away from the infant. In the second reunion, low levels of dyadic contact were complemented by slower infant movement toward the mother at the outset and throughout the reunion, as well as lower levels of infant crying. Expert rating instructions describe infants with high levels of avoidance as ignoring the mother upon her return or actively avoiding her and continuing to ignore her throughout the reunion episode (Ainsworth et al., 1978). Objective measurements partially validate this description by suggesting that high avoidance ratings reflect lower dyadic closeness, slower infant approaches to the mother, and lower levels of infant crying, as well as a corollary maternal behavior, higher mother movement away from the infant in the first reunion.

4.1.5. Disorganization

Continuous measurement of infants moving away from their mothers (velocity of moving away over both reunions) was associated with disorganization, with higher away velocities corresponding to higher disorganization. Rating scale instructions note that disorganization is indexed by the presence and frequency of unusual or contradictory behaviors including overt displays of fear, stereotypic movements, or freezing in place for an extended period (Main & Solomon, 1986). In this context, higher velocity movement away from the mother may index higher levels of fear or trepidation. Disorganization rating scales reference a multiplicity of behaviors that can occur at any point during the SSP when infant and mother are present. Despite the use of Kinect-based tracking of movement that was only present during reunions, a meaningful objective measure (velocity of movement away from the mother) accounted for a significant proportion of the variance in disorganization. Eventual tracking of movement across the entire SSP incorporating fine-grained measurements of infant expression and gesture may aid in the prediction of disorganization.

4.1.6. Dimensional measures

The dimensional measures of attachment combined expert rating scales to form two continuous characterizations of attachment security: approach/avoidance and resistance/disorganization (Fraley & Spieker, 2003). These dimensions are alternate characterizations of infant attachment. They can be compared to classic–secure, insecure-resistant, insecure-avoidant—classifications, which reflect gestalt judgments informed but not determined by expert ratings (Ainsworth et al., 1978; Ainsworth, 1979; Main & Solomon, 1986; van IJzendoorn, Schuengel, & Bakermans–Kranenburg, 1999).

Both infant and mother behavior contributed to approach/avoidance dimension scores. Continuous measures of contact duration, infant initial and overall velocity toward the mother, as well as the complementary mother features, effectively captured substantial variance in the approach/avoidance attachment dimension. Infants high on the approach/avoidance dimension were in close contact with the mother longer, and they approached her more rapidly at the start of and throughout the two reunions. Their mothers, in parallel fashion, approached the infants more quickly at the start of the reunions and moved away from them more slowly throughout.

In contrast to the approach/avoidance dimension, the resistance/disorganization dimension was predicted exclusively by infant behaviors. Continuously measured infant crying and infant movement (velocity) away from the mother captured substantial variance in the resistance/disorganization dimension. Infants high on this dimension cried for a greater proportion of both reunions and moved away from their mothers more rapidly throughout the reunions. Overall, the results suggest the promise of objectively measured infant, mother, and dyadic behaviors in capturing the two key dimensions of infant attachment behavior.

4.2. Infant-centered and dyadic objective features

Dyadic interaction can influence infant and mother behavior in both obvious and non-obvious ways. With that proviso, we conceptualized contact duration and time held as dyadic features. We conceptualized mother contact initiation, initial approach, and velocity toward and away from infant as mother-centered objective features and the parallel movement features and crying as infant-centered behaviors. Contact duration was a significant unique predictor of expert ratings in six of the nine stepwise regression models predicting individual ratings, as well as the approach/avoidance dimension. Contact duration is jointly determined by infant and mother. Either partner, for example, might move into the proximity (.8 m) of the other. While mothers might pick infants up, infants might also squirm to be put down. Although SSP rating instructions focus on infant behavior, the importance of contact duration is consonant with findings that maternal sensitivity rated *during* the SSP is associated with infant reunion behavior (Behrens et al., 2011). Behrens and colleagues found that SSP maternal sensitivity was positively associated with ratings of infant proximity-seeking and contact-maintenance, and negatively associated with rated avoidance. Together, these sensitivity findings and the current results suggest the importance of dyadic negotiation of physical closeness in predicting the broader dimension approach/avoidance dimension of attachment behavior.

In addition to the dyadic measure of contact duration, infant- and mother-centered variables had clear predictive utility in the prediction of both attachment behavior scales and attachment dimensions. Objective measures of infant approach—including initial approach and velocity toward and away from the mother—were significant predictors of all expert-rated attachment behaviors and both attachment dimensional measures. Likewise, objective measures of mother approach—including initial approach and velocity toward and away from the infant—were significant predictors of expert ratings of infant proximity-seeking, contact maintenance, and avoidance, as well as the approach/avoidance attachment dimension. In interaction, the behaviors of each partner may reflect those of the other. Nevertheless, mother and dyadic behavioral features, as well as those of the infant, made striking contributions to prediction of attachment patterns in the SSP.

4.3. Comprehensive regression prediction of expert ratings and dimensional measures

The final analytic strategy involved predicting expert ratings and dimensions of attachment using a comprehensive regression approach utilizing all objective features as predictors (Lawson & Hanson, 1995; Zeng & Ogihara, 2009). Predictors included all ten dyadic, infant, and mother movement features, as well as infant crying. Together these multimodal features explained a substantial proportion of the variance in expert ratings (see Table 7). On average, predicted values were well within one point of expert Likert ratings, suggesting their practical utility.

The comprehensive regression approach yielded particularly noteworthy levels of prediction for the dimensional measures of attachment, approach/avoidance ($R^2 = .73$) and resistance/disorganization ($R^2 = .52$), which parsimoniously capture salient indices of attachment security and may be used in lieu of the traditional classification system. Dimensional approaches to attachment suggest variations in attachment behaviors are continuous as opposed to categorical (Fraley & Spieker, 2003). These results suggest that objectively measured movement and crying in the SSP capture two key attachment dimensions which represent infants' motivations to either approach or avoid the parent, and to resist or become disorganized in the parent's presence.

4.4. Limitations and future directions

This study included a limited number of infants, only two infants with insecure-avoidant attachment styles, and no infants receiving maximum resistance or avoidance ratings (7). As larger ranges facilitate prediction, these factors highlight the need for replication with larger sample sizes containing more variable distributions of attachment ratings and classifications. Audio data were collected both from ceiling microphones and vest-worn microphones, a source difference that may have affected results. The current computer vision based approach to movement tracking benefitted from user-in-the-loop human correction. This occurred seven times per minute of video, limiting the efficiency of the tracker. Even with this user-in-the-loop, occlusions interrupted tracking such that 11 % of infant and 15 % of mother movement required interpolation, although the vast majority of occlusions were very brief (three frames or fewer). More generally, tracking captured only the overall position of infants' and mothers' heads, a significant limitation as infant hand (e.g., pick me up) and leg (e.g., stomping) gestures are an important feature of expert ratings.

While the current study reports on tracking using the original Microsoft Kinect, a new generation of trackers is now available. The Kinect 2, for example, offers researchers powerful onboard tools for tracking position, and capturing limb movements, torso sway and gait (Otte et al., 2016). Finally, more comprehensive measurement across the SSP (in the current study only the two reunions were assessed) may capture additional sources of variation in expert ratings. Thus, the current study suggests the potential for improved objective measurement approaches to better understand attachment dynamics and other interactions in future research.

This proof-of-principle report demonstrates that an objective approach to behavioral measurement can be used to effectively predict patterns of infant attachment. Theoretically informed movement and vocal features were moderately to highly predictive of expert measurements. Infant-focused measures (e.g., approaching the mother) were complemented by dyadic measures (e.g., contact duration) and mother-focused measures (e.g., approaching the infant) in predicting both expert ratings and dimensional measures of attachment. Continuous, multimodal measurement is an exciting step toward directly and transparently capturing the complexity of infant and parent attachment behaviors in the SSP. The current findings suggest the potential of available technologies in providing researchers with new tools to better understand early interaction and development.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.infbeh.2021.101565.

References

Ainsworth, M. S. (1979). Infant–mother attachment. *American Psychologist, 34*(10), 932–937. https://doi.org/10.1037/0003-066X.34.10.932.

Ainsworth, M. D. S., Blehar, M., Waters, E., & Wall, S. (1978). *Patterns of attachment: Assessed in the strange situation and at home*. Hillsdale, N.J: Erlbaum.

Avril, M., Leclère, C., Viaux, S., Michelet, S., Achard, C., Missonnier, S., … Chetouani, M. (2014). Social signal processing for studying parent–infant interaction [Technology Report]. *Frontiers in Psychology, 5*(1437). https://doi.org/10.3389/fpsyg.2014.01437.

Behrens, K. Y., Parker, A. C., & Haltigan, J. D. (2011). Maternal sensitivity assessed during the Strange Situation Procedure predicts child's attachment quality and reunion behaviors. *Infant Behavior & Development, 34*(2), 378–381.

Bowlby, J. (1982). *Attachment* (2nd ed., Vol. 1). New York: Basic Books.

Chow, S. M., Ou, L., Ciptadi, A., Prince, E. B., You, D., Hunter, M. D., … Messinger, D. S. (2018). Representing sudden shifts in intensive dyadic interaction data using differential equation models with regime switching. *Psychometrika, 83*(2), 476–510.
Ciptadi, A. (2016). *Interactive tracking and action retrieval to support human behavior analysis* (Unpublished doctoral dissertation). Atlanta, Georgia: Georgia Institute of Technology.
Dawson, G., & Sapiro, G. (2019). Potential for digital behavioral measurement tools to transform the detection and diagnosis of autism spectrum disorder. *JAMA Pediatrics, 173*(4), 305–306.
Edmunds, S. R., Rozga, A., Li, Y., Karp, E. A., Ibanez, L. V., Rehg, J. M., & Stone, W. L. (2017). Brief report: Using a point-of-View camera to measure eye gaze in Young Children with autism Spectrum disorder during naturalistic social interactions: A pilot study. *Journal of Autism and Developmental Disorders, 47*(3), 898–904. https://doi.org/10.1007/s10803-016-3002-3.
Fearon, R. P., Bakermans-Kranenburg, M. J., Van IJzendoorn, M. H., Lapsley, A.-M., & Roisman, G. I. (2010). The significance of insecure attachment and disorganization in the development of children's externalizing behavior: A meta-analytic study. *Child Development, 81*(2), 435–456. https://doi.org/10.1111/j.1467-8624.2009.01405.x.
Fraley, R. C., & Spieker, S. J. (2003). Are infant attachment patterns continuously or categorically distributed? A taxometric analysis of strange situation behavior. *Developmental Psychology, 39*(3), 387–404.
Fukuyama, H., Qin, S., Kanakogi, Y., Nagai, Y., Asada, M., & Myowa-Yamakoshi, M. (2015). Infant's action skill dynamically modulates parental action demonstration in the dyadic interaction. *Developmental Science, 18*(6), 1006–1013.
Groh, A. M., Narayan, A. J., Bakermans-Kranenburg, M. J., Roisman, G. I., Vaughn, B. E., Fearon, R. M. P., & van IJzendoorn, M. H. (2016). Attachment and Temperament in the Early Life Course: A Meta-Analytic Review. *Child Development*. https://doi.org/10.1111/cdev.12677.
Huang, D., Yao, S., Wang, Y., & De La Torre, F. (2014). Sequential max-margin event detectors. *Volume 8691 of the series lecture notes in computer science* (pp. 410–424).
Lawson, C. L., & Hanson, R. J. (1995). *Solving least squares problems: Society for Industrial and Applied Mathematics*.
Leclère, C., Avril, M., Viaux-Savelon, S., Bodeau, N., Achard, C., Missonnier, S., … Cohen, D. (2016). Interaction and behaviour imaging: A novel method to measure mother–Infant interaction using video 3D reconstruction. *Translational Psychiatry, 6*(5), e816.
Main, M., & Solomon, J. (1986). *Discovery of an insecure-disorganized/disoriented attachment pattern*.
Messinger, D. S., Mahoor, M. H., Chow, S. M., & Cohn, J. F. (2009). Automated measurement of facial expression in infant–Mother interaction: A pilot study. *Infancy, 14*(3), 285–305.
Mohan, A., Kaseb, A. S., Gauen, K. W., Lu, Y. H., Reibman, A. R., & Hacker, T. J. (2018). Determining the necessary frame rate of video data for object tracking under accuracy constraints. April. In *2018 IEEE Conference on Multimedia Information Processing and Retrieval (MIPR)* (pp. 368–371) https://engineering.purdue.edu/HELPS/Publications/papers/2018MohanMIPR.pdf.
Oller, D. K., Niyogi, P., Gray, S., Richards, J. A., Gilkerson, J., Xu, D., … Warren, S. F. (2010). Automated vocal analysis of naturalistic recordings from children with autism, language delay, and typical development. *Proceedings of the National Academy of Sciences, 107*(30), 13354–13359.
Otte, K., Kayser, B., Mansow-Model, S., Verrel, J., Paul, F., Brandt, A. U., & Schmitz-Hübsch, T. (2016). Accuracy and reliability of the kinect version 2 for clinical measurement of motor function. *PloS One, 11*(11), Article e0166532.
Perry, L. K., Prince, E. B., Valtierra, A. M., Rivero-Fernandez, C., Ullery, M. A., Katz, L. F., … Messinger, D. S. (2018). A year in words: The dynamics and consequences of language experiences in an intervention classroom. *PloS One, 13*(7), Article e0199893.
Rehg, J. M. (2013). Finding people in depth: Technical perspective. *Communications of the ACM, 56*(1), 115.
Richards, J. A., Gilkerson, J., Paul, T., & Xu, D. (2008). *The LENA automatic vocalization assessment*. LTR-08-1). Boulder, CO: LENA Foundation. Retrieved from http://www.lenafoundation.org/Research/TechnicalReports.aspx.
Sivalingam, R., Cherian, A., Fasching, J., Walczak, N., Bird, N., Morellas, V., & Papanikolopoulos, N. (2012). A multi-sensor visual tracking system for behavior monitoring of at-risk children, 14-18 May 2012 *Paper Presented at the Robotics and Automation (ICRA), 2012 IEEE International Conference*.
Turton, P., Hughes, P., Fonagy, P., & Fainman, D. (2004). An investigation into the possible overlap between PTSD and unresolved responses following stillbirth: An absence of linkage with only unresolved status predicting infant disorganization. *Attachment & Human Development, 6*(3), 241–253.
van IJzendoorn, M. H., & Kroonenberg, P. M. (1990). Cross-cultural consistency of coding the strange situation. *Infant Behavior & Development, 13*(4), 469–485.
van IJzendoorn, M. H., Schuengel, C., & Bakermans–Kranenburg, M. J. (1999). Disorganized attachment in early childhood: Meta-analysis of precursors, concomitants, and sequelae. *Development and Psychopathology, 11*(02), 225–250.
Warlaumont, A. S., Richards, J. A., Gilkerson, J., & Oller, D. K. (2014). A social feedback loop for speech development and its reduction in autism. *Psychological Science*, Article 0956797614531023.
Waters, E. (2002). *Comments on strange situation classification*. Retrieved 1/5/12 from http://www.johnbowlby.com.
Wood, C., Diehm, E. A., & Callender, M. F. (2016). An investigation of language environment analysis measures for Spanish–English bilingual preschoolers from migrant low-socioeconomic-Status backgrounds. *Language, Speech, and Hearing Services in Schools, 47*(2), 123–134.
Zeng, E., & Ogihara, M. (2009). Nonnegative least squares – A new look into SAGE data. In *Proceedings of the Eighth Annual Conference on Computational Systems Biology (CSB'09), 8* pp. 151–161).