Biological Psychology 161 (2021) 108053

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

Concordance of mother-child respiratory sinus arrythmia is continually moderated by dynamic changes in emotional content of film stimuli

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A R T I C L E I N F O

Keywords:
Physiological concordance
Mother-child interaction
Respiratory sinus arrythmia
Dynamic methods

A B S T R A C T

Evidence suggests that concordance between parent and child physiological states is an important marker of interpersonal interaction. However, studies have focused on individual differences in concordance, and we have limited understanding of how physiological concordance may vary dynamically based on the situational context. We examined whether mother-child physiological concordance was moderated by dynamic changes in emotional content of a film clip they viewed together. Second-by-second estimates of respiratory sinus arrythmia were obtained from mothers and children ($N = 158$, $M_{\text{child age}} = 45.16$ months) as they viewed a chase scene from a children's film. In addition, the film clip's negative emotional content was rated second-by-second. Results showed that mother-child dyads displayed positive physiological concordance only in seconds when there was an increase in the clip's negative emotional content. Thus, dynamic changes in mother-child physiological concordance may indicate dyadic responses to challenge.

1. Introduction

Emotional concordance is defined as congruence among multiple components of an individual's emotional functioning, namely any combination of emotional expression, behavior, cognition, and physiology (Hollenstein & Lanteigne, 2014). However, concordance has also been applied to understanding dyadic processes, examining the association of a specific component between partners. Emotional concordance between parent and child is considered an important feature of interpersonal processes (Bell, 2020; Leclère et al., 2014), suggesting that the study of dyadic concordance may be an important extension of concordance, particularly with regard to emotional development.

Most research on dyadic concordance between parent and child has focused on behavioral concordance, sometimes referred to as behavioral synchrony; it is frequently observed in mother-infant interactions (Feldman, Greenbaum, & Yirmiya, 1999) and is considered important for young children's development of emotion regulation (Harrist & Waugh, 2002). However, it is possible for parent-child concordance, or matching, of physiological states to occur even when there is no observable match in behavior. Physiological concordance has been associated with behavioral markers of healthy interpersonal functioning in parent-child dyads, such as interactive repair (Woltering, Lishak, Elliott, Ferraro, & Granic, 2015) and with positive parenting behaviors such as increased emotional availability and decreased psychological control (Han et al., 2019). Thus, understanding physiological concordance is arguably critical to our understanding of parent-child interaction and the development of children's regulatory systems (Feldman, 2012; Leclère et al., 2014).

Evidence of positive physiological concordance (i.e., increases in physiological arousal in one partner are matched by increases in the other) has been identified in interaction tasks such as free play or solving a challenging puzzle, but the adaptive value of positive concordance may differ as a function of individual differences or situational factors (e.g., Lunkenheimer, Tiberio, Skoranski, Buss, & Cole, 2018; Skoranski, Lunkenheimer, & Lucas-Thompson, 2017; Smith, Woodhouse, Clark, & Skowron, 2016; Suveg et al., 2019). On the other hand, evidence of negative concordance (i.e., increased arousal in one partner relates to decreased arousal in the other) has emerged in more high-risk contexts and have been argued to reflect either an adaptive dyadic response in the context of risk, or a maladaptive divergence in reactions to the same

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https://doi.org/10.1016/j.biopsycho.2021.108053
Received 12 October 2020; Received in revised form 20 January 2021; Accepted 15 February 2021
Available online 19 February 2021
0301-0511/

situation (Creavy, Gatzke-Kopp, Zhang, Fishbein, & Kiser, 2020; Lunkenheimer et al., 2015; Suveg et al., 2019; West, Oshri, Mitaro, Caughy, & Suveg, 2020).

Previous research has predominantly examined concordance as a stable process across an interaction task. However, it is also possible that the extent of parent-child physiological concordance varies dynamically *within* the course of an emotionally evocative situation, with moments of greater concordance and moments where individuals regulate independently. For example, physiological concordance may occur specifically at points of high negative emotional intensity to support dyadic responses to challenge, whereas dyads may react more independently at points of low emotional intensity when children may not require parental attention or support. There is evidence to suggest that parents' physiological arousal may increase when they observe their children having an emotional response to a situation (Hill-Soderlund et al., 2008; Kiser et al., 2019; Leerkes, Su, Calkins, Supple, & O'Brien, 2016), yet there is very little research on dyadic physiology that has specifically examined dynamic changes in concordance in relation to the situational context. The present study examines the extent to which mother-child physiological concordance varies over time, on a second-by-second timescale, as a function of dynamic changes in negative emotional content in a children's film clip of a chase scene that mothers and children watch together.

1.1. Physiological concordance

The research that has examined parent-child physiological concordance has focused largely on parasympathetic regulation of cardiac arousal, assessed by variability in one's heart rate across a respiratory cycle (i.e., Respiratory Sinus Arrythmia, or RSA). Parasympathetic regulation plays an important role in affective arousal and interpersonal affiliation (Porges, 2007; 2011). Specifically, parasympathetic regulation involves neural pathways that support affiliative behaviors such as facial and vocal cues, gestures, and orientation that may communicate information regarding the situation, or one's reaction to one's partner (Porges, 2007). For an individual, maintaining a higher level of RSA when there is an absence of what most observers would regard as an environmental challenge or emotional stimulus is generally considered a marker of adaptive regulation and better social functioning. Meanwhile, the myelinated vagus directly innervates the heart, facilitating rapid withdrawal and reengagement of parasympathetic cardiac control that allows individuals to respond dynamically to moment-to-moment changes in situational demands and affective intensity (Porges, 2007). A few studies have associated momentary within-person decreases in RSA (i.e., RSA withdrawal) during emotionally challenging situations with more positive parenting (Skowron, Cipriano-Essel, Benjamin, Pincus, & Van Ryzin, 2013) and better regulation of aggression in children (Miller et al., 2013), suggesting that the extent to which RSA fluctuates dynamically may be as meaningful as, or more so than, aggregated levels. Thus, parents and children may both independently show increased arousal (indexed by RSA withdrawal) during more emotionally evocative moments compared with less emotionally evocative moments, which cannot be adequately captured by average RSA levels across the task. Similarly, dyadic interaction may also be characterized by dynamic variation in the extent of concordance that cannot be captured adequately by an average concordance measure.

Such dynamic changes in dyadic concordance may be particularly meaningful in early childhood. In infancy, consistent concordance may support homeostasis and arousal modulation as young children rely on caregivers to guide social interactions (Feldman, 2012). As children enter the preschool years, they behave more autonomously as they gain motor, language, and cognitive abilities, but they may continue to depend on caregivers for support in emotionally challenging situations (Kopp, 1989). Thus, parents and preschool-aged children may not display physiological concordance constantly as it may be adaptive for children to regulate independently or have divergent reactions from their parent on occasion but show concordance in emotionally challenging moments when children require support. Evidence indicates that concordance varies in strength across different types of interaction tasks among mother-preschooler dyads (Lunkenheimer et al., 2018). However, no studies, to our knowledge, have examined variations in concordance within a task. It may be important to identify moments in which concordance may be present or more salient in the preschool years to better understand when young children require support.

Schachter (1959) posited an emotion similarity hypothesis, which states that individuals are likely to seek affiliation during fearful or threatening situations. According to the emotion similarity hypothesis, seeking affiliation or turning to others in these circumstances may be motivated by a desire to reduce one's arousal by obtaining mutual support or distraction, to gain clarity about the situation by seeking information from others, or to evaluate the nature, intensity, or appropriateness of one's own emotional reaction. The process of seeking affiliation may result in convergent emotional responses and/or appraisal of the situation, which may be reflected by positively concordant physiological reactions. As Schacter suggested, preschool-aged children may seek affiliation with their parents as the fearfulness of the stimulus increases, seeking support, information, or even referencing parents to determine how to respond. Others suggest that parents may turn to their children to provide support or comfort, help the child appraise the situation, and/or model how to respond (Bandura, 1977; Saarni, Mumme, & Campos, 1998). Given the role of parasympathetic responses in social affiliation (Porges, 2003), these responses may be reflected as positive RSA concordance in parent-child dyads in the context of fearful stimuli, even if they do not necessarily manifest behaviorally.

1.2. A dynamic approach to physiological concordance and emotional stimuli

Taken together, the available evidence indicates that physiological concordance may not be a stable characteristic of dyads but rather an aspect of their interaction that may change constantly. Therefore, we need to understand concordance as a dynamic process that should both change over time and in relation to the emotional intensity of the situation. However, tasks themselves are rarely assessed for their dynamic changes. Dynamic changes in emotional stimuli such as film clips may mimic the natural ebb and flow of real-life emotional events. For instance, empirical studies have divided a film clip into brief segments that induce different emotions (fear, sadness, happiness, and anger) and demonstrated associations between children's RSA reactivity to the different segments and internalizing and externalizing symptoms (Fortunato, Gatzke-Kopp, & Ram, 2013). Further, it may be important to consider different aspects of dynamic properties in film clips. We consider two aspects of negative emotional stimuli. First, intensity, which refers to higher levels of negative emotional content. The second is change (i.e., velocity) in negative emotional content. Drawing from a dynamic systems perspective, dyads need to flexibly re-organize behaviors to adapt to changes in the environment (Hollenstein, 2015). Increases in negative emotional content may present novel environmental perturbations that individuals and dyads need to adapt to. Studies assessing individuals' affective reactions to media content have shown, for instance, that both the level of affective content as well as the rate of increases/decreases (i.e., velocity) in content relate to affective responses (Baumgartner, Sujan, & Padgett, 1997; Teixeira, Wedel, & Pieters, 2012). Thus, we examined individual and dyadic reactions to changes in both intensity and velocity of negative emotional content in a film clip.

Examining individual and dyadic responses to dynamic properties in a film clip necessitates examining RSA on brief timescales. Although the parasympathetic system can regulate arousal on the order of seconds, typical measurement of parasympathetic activity does not have this temporal resolution. For example, RSA captures the variability in heart rate across the respiration cycle, and as such must be measured across a sufficient duration for this variability to be observed. The typical minimum measurement duration for RSA is 30 s, whereas emotion dynamics and parasympathetic activity are much more rapid (Cole, Bendezú, Nilam, & Chow, 2017; Saul, 1990). Recently, researchers have applied statistical tapering techniques in a moving-window approach to generate a second-by-second time series of RSA that reveals temporal dynamics in physiology on the level of the temporal dynamics of emotion (Gates, Gatzke-Kopp, Sandsten, & Blandon, 2015). Creavey and colleagues (2019) applied this technique to parent-adolescent dyads to examine their physiological concordance while they viewed two negative emotional film clips, one of which they watched together and the other they watched apart. Only negative concordance during the joint viewing was associated with higher levels of social empathy in adolescents, suggesting that the concordance was not merely a function of being similarly affected by the same external stimulus, but that their physiological response to the film was further influenced by one another's presence (Creavey et al., 2019). These findings illustrate a potential important level of analysis on which parents and children coordinate and respond to one another even in the absence of behavioral interaction. However, although that study employed a high temporal resolution in RSA measurement, it computed concordance across the entire task duration as a global dyadic characteristic. Thus, additional research is needed to examine the dynamic properties of concordance in the context of dynamic emotional stimuli to determine whether concordance varies as a function of changes in negative emotional content.

1.3. The current study

The current study examined the dynamics of RSA in a sample of mothers and preschool-aged children when dyads watched a frightening film clip. Children in this age range are still developing emotion regulation skills and are often reliant on parental support to cope with emotional distress. Therefore, we anticipated that parents in this context will be highly attuned to their child's emotional state in anticipation of needing to provide support. We considered how two aspects of dynamic properties of the film stimulus related to concordance, specifically, the *intensity* of negatively valanced emotionally arousing content in the film and the *change* (i.e., velocity) in emotionally arousing content. Film stimuli were continuous coded (second-by-second) for negative emotion and aligned with the second-by-second time series of parent and child RSA. First, we examined whether mothers and children independently showed changes in RSA as a result of changes in intensity and velocity in the film clip. This was also a step to validate that the film was effective in eliciting emotional responses especially in young children. We hypothesized that (H1) mothers and children would both show decreases in RSA (i.e., vagal withdrawal) in seconds when the intensity and velocity in negative emotional content is higher (vs. lower). Second, we examined whether the direction and/or strength of mother-child physiological concordance changes as a function of intensity and velocity in emotionally arousing content in the film. Consistent with Schachter (1959) emotional similarity hypothesis, we expected that physiological concordance in mother-child dyads would change dynamically across the film, specifically (H2) becoming more positively concordant when intensity and velocity of negative emotional content is higher (vs. lower). In order to verify that concordance was a property of the dyad and not merely the shared external stimulus, we also examined concordance in randomly shuffled mother-child pairs.

2. Method

2.1. Participants

Participants were 158 children (78 female) ages 30–60 months (M = 45.16, SD = 8.2) and their mothers enrolled in a study of age-related differences in early childhood self-regulation. Most children lived with two parents (89.9 %) and were identified by their parents as White (94.3 %) with the rest being identified as Asian (2.5 %), Black (1.3 %), and Native American (0.6 %), which was representative of the community in which they lived. Most of the 158 families had both parents who participated; 57 (36 %) families had only mothers who participated. Most parents (83.35 %) had at least some college education. Parents reported that they worked full-time (65.4 %) or part-time (11.95 %) or that they worked and attended school (1.85 %), attended school full or part-time (1.6 %), or were unemployed (13.8 %). The median annual income was $85,000 (range = $2000-$325,000).

2.2. Procedure

Families with children age 30–60 months were recruited through the Pennsylvania State University Child Study Center Participant database (FIRSt Families), flyers and various community events (e.g. art and craft festivals, egg hunts, and holiday festivals). Families were invited to participate in a study of young children's self-regulation. Interested families were contacted by phone and email and screened for eligibility. Inclusion criteria included: 1) the child had no known developmental or health concerns that would interfere with their providing valid data (e.g. cognitive limitations, intellectual disability, deafness), 2) the family spoke English well enough to understand and complete tasks, and 3) the parents were the child's legal guardians (e.g. biological parents, stepparents, adoptive parents). If the family met criteria and were interested, they were scheduled for a 4-h laboratory visit with their child during which trained staff administered tasks commonly used to assess child and adult self-regulation alternated with enjoyable tasks (e.g., free play, snack break).

Upon arrival to the laboratory, the family was met by a member of the research staff who outlined the visit's procedures and obtained written informed consent to participate for each parent and parental consent for the child. The research staff then recorded each family member's height and weight and applied the sensors for physiological recordings. The child and parent(s) completed a variety of tasks, sometimes alone and sometimes in pairs, during the visit. Different research assistants were responsible for administering tasks to the child alone or to a parent-child dyad, the parent-only tasks, monitoring physiological data collection and video recordings within the control room, or playing particular roles in anxiety provoking tasks (e.g., novel stranger, speech evaluator). All study procedures were approved by the Institutional Review Board at Pennsylvania State University. At the end of the visit, the family was brought together and debriefed. After the physiological sensors were removed, all the gifts the child had earned were put in a backpack that the child took home.

2.3. Fear film (little mermaid)

The first parent-child dyadic task in the laboratory visit involved mothers and children viewing a 3-minute (182 s) film clip intended to heighten fear. Prior to the start of the film and after the film ended, the dyad was shown 30 s of a silent moving star field, which facilitated assessment of pre- and post-task physiological states. Animated films are frequently used and shown to be effective in inducing negative emotions such as sadness, anger, and fear in children (Gatzke-Kopp, Jetha, & Segalowitz, 2014; Von Leupoldt et al., 2007) due to their child-appropriate content as well as the multiple congruent streams of sensory information (musical score, color scheme, facial expressions, storyline, each of which has its own robust literature base as an effective emotional stimulus) that enhance the emotional salience of the stimulus (see Lench, Flores, & Bench, 2011).

All dyads watched the same film – a chase scene from the Disney film *The Little Mermaid* in which the main characters, Ariel and Flounder, are chased by a shark. Clips, edited together to ensure that the meaning of the scene was evident, featured a dramatic plot line (e.g., characters getting in and out of danger) and presentation (e.g., drastic changes in music), and thus provided an ideal context for examining dynamic changes in dyads' physiology (Fortunato et al., 2013). Presentation and timing of the viewing (for synchronization with the electrocardiographic [ECG] recordings) was controlled by E-Prime II software (Psychological Software Tools, Inc., Sharpsburg, PA).

2.4. Measures

2.4.1. Negative emotional intensity of film

Ten research assistants who were unaware of the study purpose rated the intensity of negative emotional content of the film using the Continuous Affect Rating and Media Annotation software (CARMA; Girard, 2014). The raters used joysticks to rate the intensity of the negative emotion depicted on the screen during each second on a 0 (*not at all intense*) to 200 (*highly intense*) scale. Raters were instructed to watch the video at least once prior to rating (to become adjusted to the joystick and to avoid any surprise elements), and to then rate the content from the perspective of the main protagonists (based on assumption that most children identify with the protagonists, who are afraid), including both the negative emotions they expressed and/or level of threat they faced. Raters were asked to consider multiple aspects of the film in their ratings, including dialogue, movement, and music, to capture the overall emotional experience induced by the clip. The use of a joystick for obtaining continuous ratings of affective content in video or film stimuli has been utilized in previous research (e.g., Levenson & Ruef, 1992) and may provide more robust measures of constructs as they capture nuances in ways that discrete rating systems do not. Given excellent inter-rater reliability (ICC 3k = 0.99; Shrout & Fleiss, 1979), the *intensity* of negative emotional content in the film at each of the 182 s was calculated as the average of the 10 ratings. The extent of *velocity* in the negative emotional intensity at each second was then calculated as the first derivative (dy/dt) of the intensity time series, specifically as the difference between the intensity level of the current second and the previous second. As shown in Fig. 1a, there is considerable variability in both intensity (M = 84.91, SD = 69.71, range = 0–197.85) and velocity (M = 0.07, SD = 10.64, range = -31.05–53.24) of negative emotional content across the film, indicating the dynamic nature of the emotional stimulus.

2.4.2. Time

To account for potential linear trends in the time-series data, we included time as a within-person/dyad covariate, which was indexed as the number of seconds from the start of the film, 0–181 seconds.

2.4.3. RSA

Electrocardiography (ECG) was collected through the BioLab system (Mindware Technologies LTD., Westerville, OH) from three disposable

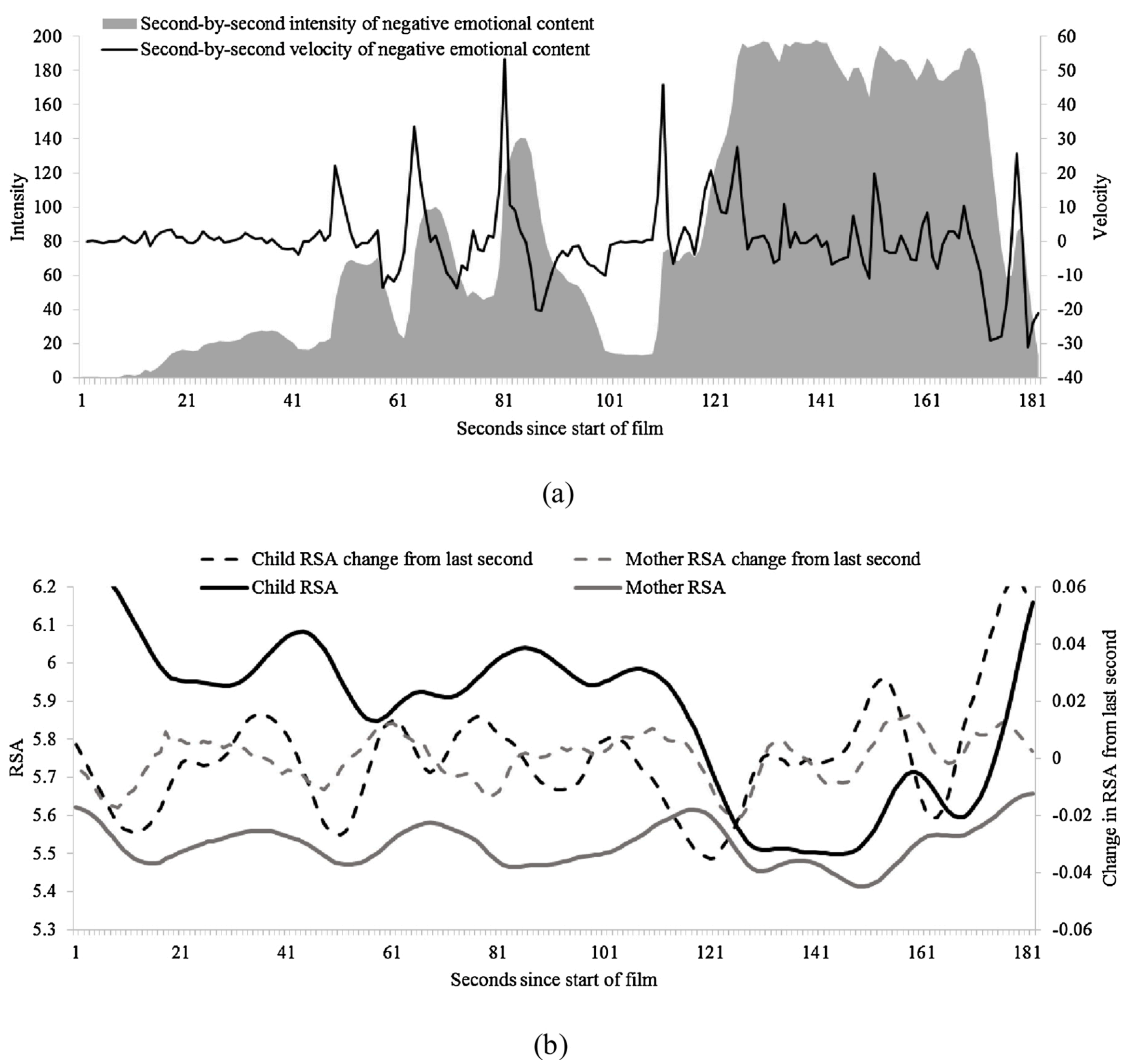

Fig. 1. Time series of the intensity and velocity of negative emotional content in the film clip (a) and sample-average child and mother RSA (b).

cardiac electrodes placed over participants' distal right collar bone, lower left rib, and lower right rib. Signals were recorded at a sampling frequency of 500 Hz. ECG data were imported into Mindware's HRV software (version 3.1.5; Mindware Technologies LTD., Westerville, OH), which automatically identified R peaks in the data stream and produced an inter-beat interval (IBI) series. Trained undergraduate research assistants visually inspected all the ECG data, and manually corrected erroneously identified or missed R peaks when the waveform could be clearly identified. In the case of lost or corrupted signals where a single beat could not be identified, the mid-beat function was used to interpolate it; when signals were lost/corrupted for a period of time comparable to two or more beats, data points between the two nearest valid beats were marked as missing. Two graduate research assistants also inspected the data to verify undergraduate research assistants' edits. Respiration rate was estimated through impedance cardiography collected through four additional electrodes and was used to verify that each participant's respiration remained within the targeted frequency band for calculating RSA (0.12−0.40 Hz for parents, and a broader range of 0.12–1.04 Hz for children; Berntson, Quigley, & Lozano, 2007). Cleaned IBI series were then output from Mindware HRV for further processing.

RSA was computed using the RHRV package (Martínez et al., 2017) in R (R Core Team, 2016). The input IBI series was first filtered for outliers based on a pre-set possible range of IBI values (i.e., 300–2000 milliseconds; which also effectively filtered large IBI values introduced by lost/corrupted signals) and algorithm embeded in the FilterNIHR function in RHRV (Martínez et al., 2017; Vila et al., 1997). Outliers were removed from the IBI series, and a separate variable tracked accumulated time in seconds across the task in order to align the IBI time series with task time, and to identify portions of task time where no cardiac data were available. From the filtered IBI data, a series of equidistant IBI values were generated at a sampling frequency of 4 Hz through cubic spline interpolation. Although the interpolation generated imputed IBI values for portions of missing/corrupted signals, we removed the interpolated values for portions of missing data that were 10 s or longer to maintain conservative precision of imputation.

Dynamic Second-by-Second RSA time-series were calculated for the entire visit using overlapping 30-second windows that each moved 1 second s forward through the interpolated, equidistant IBI series. For each 30-second window, a Hamming window taper function was applied that up-weighs the center of the window. Then, the IBI series within each window was subjected to a short-time Fourier transform to obtain a local estimate of the time-frequency distribution of power for the 15th second in the window. Second-by-second RSA was computed for each of the overlapping windows as the natural log of power within respiration frequency band. Note that this approach requires 30 s of continuous data to generate the RSA estimate for the 15th second in any given window. Because recording was initiated prior to the start of each task, estimates were available across the entire film. However, when the window encountered a segment of missing data, the ability to estimate a second-by-second RSA value was truncated 15 s prior to the missing segment and did not resume until 15 s following the missing segment. There were one child and one mother (from different dyads) whose physiological data were completely missing and excluded from analyses. Two other participants (one child and one mother, each from a different dyad) had partially missing data (10 % and 27 % of second-by-second values missing, respectively), but their available data were included in the analyses. All the other participants had complete second-by-second RSA data throughout the film task.

With interest in changes of RSA across the task, we calculated the first derivative of the RSA time-series (differences in RSA across successive seconds) and used that variable as the outcome in our analysis models. As presented in Fig. 1b, the sample's average RSA level and change both varied dynamically across the film. Furthermore, the concordance between mothers' and children's RSA changes was not constant, but rather showed different patterns in different portions of the film.

Average RSA across the task. In addition to the second-by-second estimates, the average RSA across every 30-second segment was also computed using the same technique as described above, but with non-overlapping 30-second windows that moved through the equidistant IBI series. The average RSA across the task for each participant was then calculated by averaging the 30-second RSA values, and was used in later analyses as a between-person/dyad covariate.

2.5. Data preparation and analysis

To prepare for analysis, the intensity and velocity of film negative emotional content as well as the linear time variable were all standardized ($M = 0$, $SD = 1$) for ease of interpretation in relation to the other measures under study (i.e., changes in RSA). Given the focus on within-person and within-dyad dynamics, mothers' and children's RSA changes were both centered around person means.The analyses tested whether and how mothers' and children's RSA, as well as dyads' RSA concordance, changed dynamically as a function of the intensity or velocity of negative emotional content in the film. The nested nature of the data, i.e., multiple seconds nested within dyads, was accommodated using a multilevel modeling framework. At the within-person/dyad level, time was included as a covariate to account for potential confounding effects on RSA reactivity. At the between-person/dyad level, children's and mothers' average RSA across the task, centered around sample means, was included as a covariate, to demonstrate whether the focal within-person/dyad associations were quantified by average RSA levels.

2.5.1. Dynamic changes in mother and child RSA

We tested the hypothesis that mothers and children's RSA would decrease when the intensity or velocity of negative emotional content is higher using a model (Model 1c for child and Model 1m for mother) specified as

$$\text{Child/Mother RSA change}_{it} = \beta_{0i}(\text{Time}_{it}) + \beta_{1i}(\text{Intensity}_{it}) + \beta_{2i}(\text{Velocity}_{it}) + e_{it} \quad (1)$$

The repeated measures of children's and mothers' RSA changes for individual i at second t (i.e., Child/Mother RSA change$_{it}$) were examined in separate models. Each model included time (β_{0i}), intensity (β_{1i}), and velocity (β_{2i}) as predictors, and the residual (e_{it}). RSA changes were centered around personal mean; thus, no person-specific intercept was included in the model. In turn, the person-specific coefficients were modeled as

$$\begin{aligned} \beta_{0i} &= \gamma_{00} + u_{0i} \\ \beta_{1i} &= \gamma_{10} + \gamma_{11}(\text{Child/Mother average RSA}_i) + u_{1i} \\ \beta_{2i} &= \gamma_{20} + \gamma_{21}(\text{Child/Mother average RSA}_i) + u_{2i} \end{aligned} \quad (2\text{-}4)$$

where γ_{00}, γ_{10}, and γ_{20} represented the prototypical (sample-average) within-person associations between children's or mothers' RSA changes and the time-varying predictors, Time$_{it}$, Intensity$_{it}$, and Velocity$_{it}$, respectively. Additionally, children's or mothers' average RSA across the task was included in the corresponding model as a between-person covariate, to examine whether it moderated the within-person association between intensity (γ_{11}) or velocity (γ_{21}) and RSA changes. Random effects (u_{0i}, u_{1i}, u_{2i}), which represent the between-person variations in the within-person associations, were allowed to covary with each other, but not with the time-specific residuals (e_{it}).

2.5.2. Dynamic changes in mother-child RSA concordance

We then test our hypothesis that mothers' and children's RSA reactivity becomes more positively concordant when intensity or velocity of film negative emotional content is higher using a model (Model 2) specified as:

$$\begin{aligned}\text{Child RSA change}_{it} = {} & \theta_{0i}(\text{Time}_{it}) + \theta_{1i}(\text{Intensity}_{it}) + \theta_{2i}(\text{Velocity}_{it}) \\ & + \theta_{3i}(\text{Mother RSA change}_{it}) \\ & + \theta_{4i}(\text{Time}_{it} \times \text{Mother RSA change}_{it}) \\ & + \theta_{5i}(\text{Intensity}_{it} \times \text{Mother RSA change}_{it}) \\ & + \theta_{6i}(\text{Velocity}_{it} \times \text{Mother RSA change}_{it}) + r_{it} \end{aligned} \quad (5)$$

Here, the repeated measures of children's RSA changes for individual i at second t (i.e., Child RSA change$_{it}$) were modeled as a function of time (θ_{0i}), intensity (θ_{1i}), velocity (θ_{2i}), mothers' concurrent RSA change (θ_{3i}) and its interaction with the other predictors, and residual (r_{it}). Specifically, coefficients of the interaction terms reflected how the association between mothers' and children's RSA changes varied by time (θ_{4i}), intensity (θ_{5i}), and velocity (θ_{6i}). Children's and mothers' RSA changes were centered around the personal mean. The person-specific coefficients were simultaneously modeled as

$$\begin{aligned}\theta_{0i} &= \pi_{00} + \nu_{0i} \\ \theta_{1i} &= \pi_{10} + \nu_{1i} \\ \theta_{2i} &= \pi_{20} + \nu_{2i} \\ \theta_{3i} &= \pi_{30} + \nu_{3i} \\ \theta_{4i} &= \pi_{40} \end{aligned} \quad (6\text{-}12)$$

$$\theta_{5i} = \pi_{50} + \pi_{51}(\text{Child average RSA}_i) + \pi_{52}(\text{Mother average RSA}_i)$$
$$\theta_{6i} = \pi_{60} + \pi_{61}(\text{Child average RSA}_i) + \pi_{62}(\text{Mother average RSA}_i)$$

where π_{00} to π_{60} represent the prototypical (i.e., sample-average) within-person associations. For instance, π_{30} describes the association between a mother's and child's concurrent RSA changes, and π_{60} describes how that association was moderated by the velocity of negative emotional content for the prototypical dyad in this sample. Children's and mothers' average RSA across the task were included as between-dyad covariates to examine whether the dynamic changes in RSA concordance by intensity (π_{51} and π_{52}) and velocity (π_{61} and π_{62}) were moderated by individual differences in average RSA levels. Random effects were specified for the four main effect coefficients (ν_{0i}, ν_{1i}, ν_{2i}, ν_{3i}); these random effects were allowed to covary with each other, but not with the time-specific residuals (r_{it}).

Follow-up tests were used to validate that the RSA concordance was driven by dyadic processes, rather than other potential confounds, such as increased attention to the film when intensity or velocity of negative emotional content is higher. Here, we fit the same model to synthetic data that were constructed by randomly pairing mothers and children (Model 3).

All models were fit to the 28,475 repeated measures nested within 158 dyads using the *nlme* package (version 3.1–148; Pinheiro, Bates, DebRoy, Sakar, & R Core Team, 2017) in R (R Core Team, 2016), with restricted maximum likelihood estimation and with incomplete data treated using standard missing-at-random assumptions. Statistical significance was evaluated at $\alpha = 0.05$.

3. Results

3.1. Dynamic changes in mother and child RSA

The first hypothesis that intensity and velocity of negative emotional content in the film clip would be associated with individuals' second-by-second RSA changes was supported with children's data, but not with mothers' data. In Model 1c for the children's RSA change outcome (see Table 1), there was a significant linear effect of time, such that children showed increases in RSA with the passage of time ($\gamma_{00} = 0.0133$, $p < .01$ in Model 1c). After controlling for the linear time trends, the second-by-second intensity and velocity of film negative emotional content were both related to children's concurrent RSA changes. As hypothesized, children were more likely to show decreases in RSA during seconds when (a) the level of film negative emotional intensity was higher ($\gamma_{10} =$ -0.0095, $p < .01$ in Model 1c) and (b) there was an increase in film negative emotional intensity ($\gamma_{20}=$ -0.0034, $p < .01$ in Model 1c). These within-person associations did not vary across children as a function of their average RSA during the task ($\gamma_{11} =$ -0.0011 and $\gamma_{21} =$ -0.0006, $ps >$ .05 in Model 1c).

Table 1
The intensity and velocity of negative emotional content during the film clip predicting children's or mothers' RSA changes.

	Model 1c Child RSA change		Model 1 m Mother RSA change	
Fixed Effect	Estimate (*SE*)	*p*	*Estimate (SE)*	*p*
γ_{00} (Time)	**0.0133** (0.0016)	< .01	**0.0048** (0.0020)	.02
γ_{10} (Intensity)	**−0.0095** (0.0017)	< .01	−0.0035 (0.0021)	.08
γ_{20} (Velocity)	**−0.0034** (0.0006)	< .01	−0.0008 (0.0007)	.26
γ_{11} (Intensity × Average RSA)	−0.0011 (0.0006)	.22	**−0.0023** (0.0006)	< .01
γ_{21} (Intensity × Average RSA)	−0.0006 (0.0005)	.05	0.0009 (0.0006)	.12
Random Effect Standard deviation	Estimate	95 % *CI*	Estimate	95 % *CI*
$\sigma_{u_{0i}}$ (Time)	0.0186	[0.0163, 0.0212]	0.0229	[0.0200, 0.0263]
$\sigma_{u_{1i}}$ (Intensity)	0.0196	[0.0172, 0.0223]	0.0236	[0.0206, 0.0269]
$\sigma_{u_{2i}}$ (Velocity)	0.0057	[0.0047, 0.0069]	0.0066	[0.0053, 0.0083]
σ_e (Residual)	0.0634	[0.0629, 0.0639]	0.0836	[0.0829, 0.0843]
Correlation				
$\rho[u_{0i}, u_{1i}]$	−0.9472	[-0.9664, -0.9175]	−0.9504	[-0.9693, -0.9202]
$\rho[u_{0i}, u_{2i}]$	0.2920	[0.0507, 0.5011]	0.2568	[-0.0478, 0.5178]
$\rho[u_{1i}, u_{2i}]$	−0.2884	[-0.4938, -0.0525]	−0.2331	[-0.5044, 0.0801]

Note. CI = Confidence interval. Statistically significant fixed effect coefficients were bolded.

In Model 1 m in which mothers' RSA was examined (see Table 1), there was a significant linear effect of time as well, with mothers also showing increases in RSA with the passage of time ($\gamma_{00} = 0.0048$, $p = .02$ in Model 1m). After controlling for the time effect, mothers' second-by-second RSA changes were on average not significantly associated with the intensity (γ_{10} = -0.0035, p = .09 in Model 1m) or velocity (γ_{20}= -0.0008, p = .26 in Model 1m) of film negative emotional content. However, mothers' average RSA during the task moderated the within-person association between intensity and their moment-to-moment RSA changes, such that mothers with higher average RSA showed greater RSA decreases when the level of film negative emotional intensity was higher (γ_{11} = -0.0023, $p < .01$ in Model 1m). Mothers' average RSA did not moderate the association between velocity and momentary RSA changes (γ_{21} = 0.0009, $p = .12$ in Model 1m).

3.2. Dynamic changes in mother-child RSA concordance

Our second hypothesis also received partial support. Specifically, we hypothesized that concordance between mothers' and children's RSA changes would vary dynamically as a function of the intensity and velocity of the film's negative emotional content. Table 2 reports estimates of two models, one using correctly paired mother-child dyads' data (Model 2), and the follow-up contrast case using synthetic data created by randomly pairing mothers and children (Model 3). For the correctly paired data, there was no evidence of dyadic RSA concordance at the average intensity and velocity of film negative emotional content (π_{30} = 0.0131, $p = .41$ in Model 2), and contrary to our hypothesis, the film's negative emotional intensity did not moderate mother-child RSA concordance ($\pi_{50} = 0.0075$, $p = .33$ in Model 2). However, in line with our hypothesis, the velocity of film negative emotional content did

Table 2
The intensity and velocity of negative emotional content during the film clip moderating the concordance between children's and mothers' RSA changes.

	Model 2 Correctly paired dyads		Model 3 Randomly paired dyads	
Fixed Effect	Estimate *(SE)*	*p*	Estimate *(SE)*	*p*
π_{00} (Time)	**0.0130** (0.0016)	< .01	**0.0132** (0.0017)	< .01
π_{10} (Intensity)	**−0.0094** (0.0017)	< .01	**−0.0093** (0.0017)	< .01
π_{20} (Velocity)	**−0.0033** (0.0006)	< .01	**−0.0032** (0.0006)	< .01
π_{30} (Mother RSA change)	0.0131 (0.0158)	.41	0.0247 (0.0165)	.13
π_{40} (Time × Mother RSA change)	−0.0104 (0.0079)	.17	0.0075 (0.0079)	.34
π_{50} (Intensity × Mother RSA change)	0.0075 (0.0077)	.33	0.0061 (0.0076)	.42
π_{60} (Velocity × Mother RSA change)	**0.0124** (0.0048)	.01	−0.0035 (0.0047)	.46
π_{51} (Intensity × Mother RSA change × Child average RSA)	0.0015 (0.0041)	.72	0.0001 (0.0042)	.99
π_{52} (Intensity × Mother RSA change × Mother average RSA)	0.0064 (0.0039)	.10	0.0023 (0.0041)	.58
π_{61} (Velocity × Mother RSA change × Child average RSA)	−0.0034 (0.0040)	.39	0.0045 (0.0040)	.25
π_{62} (Velocity × Mother RSA change × Mother average RSA)	−0.0007 (0.0040)	.86	0.0016 (0.0039)	.68
Random Effect Standard deviation	Estimate	95 % CI	Estimate	95 % CI
$\sigma_{v_{0i}}$ (Time)	0.0174	[0.0157, 0.0196]	0.0178	[0.0160, 0.0201]
$\sigma_{v_{1i}}$ (Intensity)	0.0179	[0.0161, 0.0202]	0.0188	[0.0169, 0.0212]
$\sigma_{v_{2i}}$ (Velocity)	0.0048	[0.0043, 0.0054]	0.0042	[0.0038, 0.0047]
$\sigma_{v_{3i}}$ (Mother RSA change)	0.1744	[0.1568, 0.1964]	0.1831	[0.1646, 0.2063]
σ_r (Residual)	0.0614	[0.0552, 0.0692]	0.0611	[0.0550, 0.0689]
Correlation				
$\rho[v_{0i}, v_{1i}]$	−0.9543	[-0.9666, -0.9376]	−0.9580	[-0.9694, -0.9426]
$\rho[v_{0i}, v_{2i}]$	0.2546	[0.1000, 0.3973]	0.3661	[0.2197, 0.4964]
$\rho[v_{0i}, v_{3i}]$	0.2056	[0.0485, 0.3528]	0.0521	[-0.1080, 0.2095]
$\rho[v_{1i}, v_{2i}]$	−0.2491	[-0.3922, -0.0941]	−0.3425	[-0.4758, -0.1939]
$\rho[v_{1i}, v_{3i}]$	−0.1506	[-0.3020, 0.0083]	−0.0158	[-0.1745, 0.1438]
$\rho[v_{2i}, v_{3i}]$	0.2622	[-0.1080, 0.4040]	−0.0980	[-0.2533, 0.0621]

Note. CI = Confidence interval. Statistically significant fixed effect coefficients were bolded.

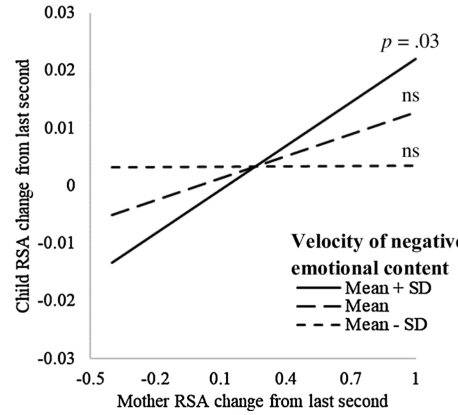

Fig. 2. The concordance between mothers' and children's RSA changes at different velocity in negative emotional content of the film clip.
Note. SD = Standard deviation. As displayed in Fig. 1, velocity of negative emotional content ranged from -31.05–53.24; the unstandardized values for mean, mean + 1SD, and mean – 1SD of the moderator were 0.07, 10.71, and -10.57, respectively.

moderate mother-child RSA concordance (π_{60} = 0.0124, p = .01 in Model 2). We probed the interaction by plotting the association between mothers' and children's RSA changes for the mean of velocity and for 1 *SD* above and below the mean (i.e., standardized velocity = 0, 1, and -1, and unstandardized velocity = 0.07, 10.71, and -10.57) and examining the corresponding simple slopes. As shown in Fig. 2, positive concordance between mothers' and children's RSA changes occurred only when there were greater increases in the film's negative emotional intensity. How RSA concordance changed within dyads as a function of intensity or velocity was not moderated by children's or mothers' average RSA (none of π_{51}, π_{61}, π_{52}, π_{62} was statistically significant in Model 2).

In the follow-up test (Model 3), the estimates reflecting how children's RSA changed as a function of time, intensity, and velocity (π_{00} to π_{20}) remained consistent with those in Model 2. However, after the dyadic pairing was shuffled, the moderation effect representing how mother-child RSA concordance changed as a function of velocity was not present (π_{60}= -0.0014, p = .77 in Model 3). Similar to Model 3, how RSA concordance changed as a function of intensity or velocity of negative emotional intensity was not moderated by children's or mothers' average RSA during the task (none of π_{51}, π_{61}, π_{52}, π_{62} was statistically significant in Model 4).

4. Discussion

The aim of examining variations in parent-child physiological concordance as a function of a changing stimulus has potential to provide deeper understanding of how parents and children respond individually, and importantly how they respond conjointly, as negative emotional intensity in a stimulus increases. Specifically, we investigated whether RSA concordance between mothers and their young preschool age children increased in relation to changes in the negative emotional intensity of a fear-eliciting film clip. This was the first study, to our knowledge, to explicitly examine dynamic changes in mother-child physiological concordance as a function of a dynamic emotional stimulus.

Our findings first revealed that children's RSA was responsive to the emotional dynamics of the film, but that mothers' RSA was not. Polyvagal theory (Porges, 2007) proposes that vagal withdrawal reflects an increase in physiological arousal needed to support active coping and responding to environmental challenges. Both greater intensity and velocity in negative emotional content may represent an environmental challenge for young children, resulting in increased physiological arousal in response to both higher levels of negative emotional content as well as new perturbations in the emotional stimulus. By contrast, mothers' physiological states may be more responsive to anticipated or perceived changes in their children's reactions to the film rather than the film content itself. The possibility that mothers respond to their children rather than the film is further supported by our finding that dyadic physiological concordance emerged as the negative emotional intensity of the film increased. To consider this explanation, we tested randomly paired dyads, which enabled us to investigate reactivity patterns to changes in emotional intensity in unrelated mothers and children. A lack of concordance among the randomly paired dyads indicates that the emergence of concordance occurred in only related mothers and children who were watching the film together and suggests that mothers' physiological state changes were related to their anticipation of or response to children's reactions to the building drama of the chase scene and not the scene itself. This opens the door to additional questions. For example, it is possible that mothers' physiological changes in RSA reflect their readiness to act in a regulatory capacity at times when their children may experience an increase in emotional arousal.

Interestingly, physiological concordance was not observed as a function of intensity in negative emotional content, but rather as a function of velocity, that is, *increases* in intensity. That is, the concordance was responsive to changes in the stimulus, and specifically increases in negative emotional intensity. In moments where the negative emotional content in the film was increasing positive concordance increased, whereas in moments when emotional intensity was stable or decreasing concordance decreased. The specificity of this finding to the change in negative emotional intensity suggests that mother-child physiological concordance emerges at the point when a new challenge is faced. Even at moments when the emotional intensity remains high, concordance was reduced if the velocity was low, possibly because the child did not need to adapt to new or intensifying challenges and the mother did not need to respond. This finding underscores the value of coding film stimuli to examine how individual and dyadic physiological changes relate to different aspects of emotional challenges. It may be important to examine parent-child physiological processes in moments of environmental perturbation, such as increases in negative emotional content, to better understand dyadic responses to challenge.

Increases in negative emotional content in this film clip presented a heightened level of fear that required some physiological adaptation by mother-child dyads. Drawing from Schacter's (1957) emotional similarity hypothesis, mothers and children show increased physiological concordance when the environment presents greater fear or threat; children may engage in social referencing during these seconds (Saarni et al., 1998), looking to mothers to provide information on how to react and interpret increases in negative emotional content and mirroring mothers' responses. Mothers may model emotion regulation strategies such as staying calm or reframing the situation (or potentially maladaptive ones such as minimizing or suppressing negative emotions), and children may imitate these responses (Bandura, 1977). Social referencing and modeling may be reflected by greater positive physiological concordance even in the absence of behavioral interaction, as non-verbal cues may also convey emotional reactions. However, future research should include observational or electromyographical measures of parents' and children's behaviors and emotional expressions, to understand whether changes in physiological concordance are accompanied by behavioral responses such as orienting to one another, facial expressions, or verbalizations. It is also important to note that the positive concordance observed in this study may have positive implications for children's emotion regulation particularly at this developmental stage. Mothers are primarily responsible for teaching preschool-aged children how to manage negative emotions and may be more attuned or responsive to children's emotional reactions. However, it is possible that the benefits of this type of concordance would diminish as children age and take on increasing responsibility for their own regulation. For instance, positive concordance when viewing a sad film clip together has been shown to reflect maladaptive patterns of interaction in parent-adolescent dyads (e.g., Creavy et al., 2020).

Dynamic changes in physiological concordance also imply that in the absence of a new emotional challenge, lack of concordance may provide children opportunities to respond independently or diverge from the parent in their reactions. However, when new challenges are faced, young children may require attention and support from parents. Thus, it is possible that patterns of *variation* in physiological concordance across interactions are a more important indicator of parent-child interaction quality in this age group. Previous research has shown that both strength and direction of physiological concordance across interaction contexts varies as a function of children's behavior problems, maternal emotional functioning, or dyadic characteristics such as attachment style (e.g., Creavy et al., 2020; Davis, West, Bilms, Morelen, & Suveg, 2018; Lunkenheimer et al., 2018; Smith et al., 2016; Suveg et al., 2019; Woody, Feurer, Sosoo, Hastings, & Gibb, 2016). An important next step in integrating this literature would be to understand how these individual differences may interact with dynamic changes in stimuli to predict patterns of physiological concordance. For instance, it is possible that parents and children with psychopathological symptoms may struggle with responding to increased environmental threat or challenge, compared to moments with the absence of challenge. Adopting a dynamic approach to examining concordance with at-risk dyads can help us better identify specific instances and corresponding situational demands in which these dyads may experience difficulties in interaction.

It is important to note that the participants in this sample were fairly homogeneous, identifying predominantly as White, educated, and economically stable. Research demonstrates cultural differences in parenting styles, practices, and norms and expectations about emotion and emotional socialization (Raval & Walker, 2019). However, the findings indicate the value of a dynamic approach, particularly one that links environmental changes to changes in physiology, both individual and dyadic. It would be interesting to document the extent of this finding across different situational stimuli and among parent-child dyads in families with more diverse structures (e.g., adoptive and/or same-sex parents) or from more diverse cultural backgrounds, where there may be different norms and challenges related to emotion and socialization.

Furthermore, the current study only examined concordance over the course of one fear-inducing film task, and thus it is unclear whether changes in emotional intensity have implications for concordance in different emotional contexts (e.g. sad, happy). However, given the importance of context on the presence, strength, and direction of parent-child concordance, it is important for future research to compare patterns of physiological concordance across contexts to determine the conditions under which concordance occurs and what factors are related to various patterns of physiological concordance. We utilized a short film clip to create emotionally salient changes in the environment and watching film clips together may provide a situation for parents to help children learn how to appraise and respond to fearful or threatening stimuli. However, a task that presents a more direct threat to the dyad (e.g., a scary object or strange situation) may better mimic challenges dyads face. Perhaps threatening tasks elicit stronger emotions and, thus, different patterns of physiological concordance may emerge than those we observed in our study. In addition, the present study did not examine the implications of concordance for children's emotional development, and these findings should not be interpreted to reflect an inherently normative or adaptive dyadic characteristic. Our findings can only speak to the timescale at which concordance is changing.

Despite these limitations, this study makes important contributions to our understanding of physiological concordance. We utilized an innovative coding system to rate negative emotional content in a film clip to examine changes in parent-child physiological concordance as a function of fluctuations in the emotional content. Further, extending previous research (e.g., Creavy et al., 2020; Gates et al., 2015), we demonstrate that parasympathetic reactivity in children and dyads fluctuate on a second-by-second timescale. Finally, our results show that parent-child physiological concordance is a dynamic rather than a stable process and may be more evident in the context of increases in negative emotional content in the environmental stimulus. Thus, it is especially important to examine dynamics of parent-child physiological concordance during transitions or changes in the environment that are increasingly challenging to better understand dyadic emotion socialization processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work reported in this article was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development under award number R01HD076994. The content is solely the responsibility of the authors and does not necessarily represent the official view of the National Institutes of Health.

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