CONTRIBUTIONS OF PHYSIOLOGICAL AND BEHAVIORAL SYNCHRONY TO THE PREDICTION OF TASK PERFORMANCE IN A MOTHER-CHILD DYADIC PUZZLE TASK

by

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(Under the Direction of Drew H. Abney)

ABSTRACT

Conceptualizing development as a complex system of interactions allows researchers to measure the unique contribution of physiological and behavioral factors to a variable of interest across levels of analysis. Past research suggests that positive respiratory sinus arrhythmia (RSA) and interpersonal movement synchrony (IMS) are associated with higher levels of emotion regulation and task performance in mother-child dyads. However, the unique contribution of each measure of synchrony is currently understudied. This study explores the relationships between IMS, RSA synchrony, and performance on a puzzle task as a preliminary investigation into the systemic interactions between physiology, behavior, and problem-solving. The sample included 39 biological mothers (M_{age} = 35.13, *SD* = 7.11) and their children (M_{age} = 6.10, *SD* = 0.79). Results found no evidence of either IMS or RSA synchrony, suggesting that neither explains significant variability of task performance. This research contributes to understanding the development of problem-solving and spatial awareness through mother-child interactions.

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DEDICATION

To my partner, Mel.
You mean the world to me.
I’m so excited to grow with you.

To our daughter, Ivy.
You mean the world to me.
I’m so excited to meet you.

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CHAPTER 1

INTRODUCTION

Through the lens of complex systems theory (CST), an individual is conceptualized as a complex system who interacts with others and the environment to produce changes that are then re-incorporated into the system (Dooley, 1997; Eidelson et al., 2017). In simpler terms, individuals influence their environments while their environments simultaneously influence them. Dynamical Systems Theory (DST) furthers the conceptualization posed by CST by suggesting that systems of human behavior are dynamical systems. Dynamical systems are continuously acting and being acted upon across multiple timescales and levels of analysis (Thelen & Smith, 2006). Small-scale actions can have large-scale effects and these effects can be linear or nonlinear. These systems theories allow the study of human development to focus not solely on the causality of behavior and outcomes, but also on the unique variance that multiple interactions contribute to stages of development.

Untangling systems of human development entails understanding the human system and its change over time. As children develop, they obtain abilities that fundamentally alter their perception and interaction with the world. Changes in motor skills, behavior, and personality adjust the parameters of exploring and understanding the world. A child who can walk is going to have a fundamentally difference experience when compared to one who is still crawling (Adolph & Franchak, 2017; Kerr, 2021; Kretch et al., 2014): not only can a walking child travel greater distances, but their field of vision is wider, and they can interact with toys and objects that would be out of reach for the crawling child (Franchak et al., 2018). Furthermore, development in a single area, like motor development, has a cascading effect on other developmental domains. (Bradshaw et al., 2022). For example, infants who are walking have a completely different set of social and communicative possibilities when compared to pre-walking infants, which can lead to the emergence of behaviors like social referencing and triadic interactions (Bradshaw et al., 2018; Campos et al., 2000). Motor and social skills are only two of various interconnected domains that interact and contribute to development by influencing the child's ability to interact with their environment. By understanding the role and interactions of each domain in the growth of infants and children, we paint a clearer picture of each domain and the child's development.

Children's developmental growth is also fundamentally linked to their relationships with the people in their life, like parents, siblings, teachers, and peers. From as early as infancy, children pay attention to people to learn a wide assortment of skills like communication and emotional regulation (Abney et al., 2021; Farroni et al., 2002). As children age and develop, the complexity of these interactions only increases, such that even simple activities can provide opportunities for growth and development. For example, when parents and children aged 3-7 work together on puzzles, parents can provide verbal assistance, scaffolding, or spatial language, each of which has been found to be positively associated with children's spatial awareness (Casasola et al., 2020; Levine et al., 2012; Thomson et al. 2020). Spatial awareness is a positive predictor of STEM and mathematics scores in school, emphasizing the cascading importance of cooperative puzzle work in a child's life (Pyers et al., 2010; Utal & Cohen, 2012; Verdine et al., 2017). However, the variability in how parents and children approach cooperative puzzle tasks is large and understudied, such that the type, number, and difficulty of puzzles can influence the type, amount, and level of interaction a parent has in cooperative play (Pochinki et al., 2021). Untangling the variability of parent-child puzzle tasks therefore has the potential to lead to a greater understanding of naturalistic parent-child interactions and their relationship with development across multiple domains.

By using CST and DST we have a theoretical foundation and a set of quantitative tools that allows us to view child development as the result of complex interactions with their environments and social interactions. By focusing on a particular age and type of interaction, we can better understand the cascading relationship between interactions and development across domains. In the present study, I examine both behavioral and physiological interactions between parents and children to better understand how these systems interact, synchronize, and contribute to performance in a puzzle task.

Interpersonal Synchrony

Interpersonal synchrony has been defined as the concordance of behaviors, emotions, and physiological processes in time between two or more individuals (Bernieri & Rosenthal, 1991; Palumbo et al., 2017). Positive synchrony refers to changes that occur together in the same direction (*e.g., heart rate increasing at the same time*) while negative synchrony refers to spontaneous changes that occur in tandem but in the opposite direction (*e.g., heart rate increasing in one person while decreasing in the other person*). The effect of synchronization is varied across a variety of factors including but not limited to age, gender, and relationship between the synchronizers (Feldman et al., 2003). In infancy and toddlerhood, mother-child positive behavioral synchrony contributes to the development of a child's self-regulation and empathy (Feldman, 2007; Kochanska et al., 2008). However, other evidence points toward negative effects of interpersonal synchrony (Palumbo, 2017). For example, emotional synchronization during conflict is associated with negative influencing behaviors and lower relationship satisfaction in couples (Butler, 2015). This indicates that synchrony varies across type, measurement, environment, and the context of the relationship between individuals.

Synchrony can be broadly classified into one of two categories, either behavioral or physiological synchrony, both of which can be further broken down into specific measures. Behavioral synchrony consists of any behaviors or displayed emotions from individuals and includes affect, vocalizations, and movements. Physiological synchrony is the temporal matching of neural, hormonal, or Autonomic Nervous System (ANS) responses between individuals. Each distinct measure of synchrony potentially contributes unique variance to the development of the developmental system (Birk, 2022). In the context of families, Feldman's BioBehavioral Model of Synchrony addresses the importance of both behavioral and biological factors in synchronous interactions with both parents, suggesting that both types of synchronies develop in early infancy and develops along with the child and parent (Feldman, 2014a). While an individual measure of synchrony may provide insights into behavior, it is hypothesized that additional measures of synchrony provide unique insights into families.

Synchrony across behavioral and biological systems emerges differently based on type, relationship, and task context. It is therefore possible for a dyad to be synchronized in more than one way at a time, with different measures of synchrony emerging during different types of tasks. Reindl and colleagues found that physiological and neural synchrony emerged during cooperative, but not competitive tasks, while synchronization of motor behavior did not (Reindl et al., 2022). The exact nature of these interactions has yet to be fully explored and requires intentional research to delineate. Multi-modal synchrony is the collection of multiple measures of both behavioral and physiological synchrony to determine the unique variance each measure contributes to an outcome. This is especially important given the context-dependent results of studies of interpersonal synchrony (Abney et al., 2021; Paxton et al., 2014; Tal et al., 2023). Data collection from physiological and behavioral modalities concurrently is consistent with Feldman's BioBehavioral Model of Synchrony (Feldman, 2014a) and will provide insights into the significance of multiple interactions within systems. In the current study, we focus on two specific measurements of interpersonal synchrony – respiratory sinus Arrythmia (RSA) and interpersonal movement synchrony (IMS). Studying synchrony in the context of puzzle task performance will expand our understanding of the interaction between parent-child interaction and child development and potentially elucidate the variability between groups of parents and the different types of synchrony.

Respiratory Sinus Arrythmia

Respiratory sinus arrythmia (RSA) is a measure of cardiac vagal tone derived from heart rate variability at the frequency of respiration (Abney et al., 2021; Bernston et al., 1997; Porges, 2007). RSA is used to study the regulation of the parasympathetic nervous system (PNS) via the vagus nerve and the vagal brake. The vagus nerve regulates the PNS by releasing the vagal brake to allow the somatic nervous system (SNS) to calm an individual. When necessary, the vagus nerve also increases metabolic output via vagal withdrawal to prepare an individual to act. This regulation contributes to cardiac activity such that an increase in vagal control slows heart rate to calm, while a decrease in vagal control speeds up heart rate to support mobilization (Porges, 2007). RSA synchrony occurs when there is temporal coordination of vagal stimulation or vagal withdrawal between individuals. RSA synchrony is highly context-dependent and can be moderated by contextual risk conditions (e.g., parent/child symptoms of psychopathology) as well as parental attitudes (Davis et al., 2018; Lunkenheimer et al., 2018; Lunkenheimer et al., 2021; Miller et al., 2022; Olson et al., 2005). In mother-child dyads, the relationship between RSA synchrony and task performance is currently unexplored.

Movement Synchrony

Interpersonal Movement Synchrony (IMS) is the temporal coordination of gross (broad, overarching) or fine (small, muscular) body movements (Koul et al., 2023). IMS consists of movements above and beyond mimicry or gesturing and can emerge from eye contact without need for a structured social task (Koul et al., 2023). IMS activates across the entire body and synchronization in different parts of the body has potential to result in different outcomes. In psychotherapy, the existence of IMS in head movements between adult patients and their therapists has been shown to predict the satisfaction with therapy across multiple sessions, while synchronous body movements predicted individual session outcomes (Ramseyer & Tschacher, 2014). Movement synchrony also occurs across timescales, responding to both long-term slow environmental factors (*high-level constraints*) as well as fast changes in environmental context (*low-level constraints*) (Paxton & Dale, 2017). Movement has historically been analyzed either through accelerometry or through behavioral coding of video recordings. Recent research has developed and verified multiple measures of movement synchrony using video cameras, including using changes in pixel density for each frame and machine-learning approaches to label and classify positions based on hand-labeled markers (Fujiwara et al., 2020; Paxton & Dale, 2013). When operationalized as a measure of postural sway, lower levels of synchrony in child-child dyads can predict higher puzzle performance scores (Vink et al., 2017). In cooperative tasks, positive IMS measured with a pixel-density approach is associated with better social play behaviors in children, and higher positive affect in cooperative tasks (Tscacher et al., 2014; Tunçgenç & Cohen, 2016). In father-child interactions, specifically, higher levels of positive movement synchrony predict lower levels of child anxiety, but the dynamics of IMS in mother-child dyads and task performance are currently unexplored (Roman-Juan et al., 2020).

The Current Study

Following the Dynamical Systems Theory and BioBehavioral Model of Synchrony, we aim to identify unique contributions of behavioral and physiological synchrony on cooperative task performance in mother-child dyads. The Tangram task is a short shape-match task that alternates between cooperative and individual conditions, with a short rest between each set of puzzles. Tangram task performance has been associated with both behavioral and physiological synchrony. Specifically, higher levels of positive neural synchrony and lower levels of postural sway synchronization between mothers and children predict higher cooperative performance in the Tangram task (Nguyen et al., 2020; Vink et al., 2017). This indicates a context-specific interaction that is best understood through a multi-modal design. While other measures of behavioral and physiological synchrony are associated with maternal bonding, team cohesion, and broad performance, their relationship with the Tangram task has yet to be explored (Feldman et al., 1999; Monster et al., 2016).

By examining both RSA and IMS synchrony simultaneously, I will assess whether each measure of synchrony is uniquely predictive of performance in the Tangram task. Specifically, I hypothesize:

Hypotheses

1a: RSA synchrony will emerge between mother and child during the cooperative, but not individual Tangram task.

1b: Interpersonal movement synchrony will emerge between mother and child during the cooperative, but not individual Tangram task.

2a: Positive RSA synchrony will be positively associated with mother and child's number of successfully completed puzzles (Tangram scores).

2b: Interpersonal movement synchrony will be positively associated with mother and child's number of successfully completed puzzles.

3: (Exploratory) RSA and Movement synchrony will each contribute unique variance to the prediction of Tangram scores

CHAPTER 2

METHOD

Participants

The current study included data from a larger multi-modal data collection examining the relationship between stress, physiology, behavior, and emotional self-regulation in mother-child dyads. Participants included 80 mothers (M_{age} = 35.21, *SD* = 7.21) and their children (M_{age} = 5.89, *SD* = 0.80), 46% Male, 54% Female). Of this sample, only 39 dyads (Mothers: M_{age} = 35.13, *SD* = 7.11; Children: M_{age} = 6.10, *SD* = 0.79) had usable movement and RSA data. 19 dyads were removed due to issues in properly tracking movement. An additional 15 dyads were removed due to incomplete movement data (NAs) for either parent or child, making it impossible to calculate synchrony. The remaining dyads were removed due to missing RSA data. Tables 1-4 display demographics (race/ethnicity, income, and age) of the sample. Parents selected race/ethnicity from a list with an "Other" option to ensure inclusion. Income was determined from a survey that asked for the yearly household income from 0-100k in increments of $20,000. Any value over 100k was inputted as "Over 100k" in the survey. Age was requested as a numerical value in the survey. Inclusion criteria were that mothers and their children were both fluent in English, children were between the ages of five-years-old and seven-years-old and had no diagnosed developmental disability. Partway through data collection, an additional inclusion criterion assessed whether either the mother or child identify as part of an underrepresented racial or ethnic group. This inclusion criterion was added to ensure a diverse sample that better represented the Athens, Georgia community.

Procedures

All study procedures were done in accordance with and approved by the University of Georgia's Institutional Review Board (IRB). Data were collected as part of a larger study examining behavioral and physiological markers of stress in predicting a child's self-regulation. Participants were recruited through a combination of local events around Athens, Georgia, and online recruitment through Facebook groups.

Parents were assessed for eligibility over the phone and scheduled for a 2-hour lab visit upon meeting the inclusion criteria. During the visit, participants first provided consent through a Qualtrics form and verbal assent was provided from the children and confirmed by their mother. Next, parents completed several questionnaires, all of which were administered via an iPad through the Qualtrics platform. Following the completion of questionnaires, parents and their children were escorted to the main study room where they were equipped with wireless Electrocardiogram (ECG) belts to collect inter-beat intervals (IBIs), from which RSA is derived. Participants were also video recorded throughout all experimental phases, which lasted approximately one hour.

Procedures began with a 2-minute video, during which participants' baseline levels of RSA were collected. Participants subsequently completed a LEGO task, 20 minutes of free play, and finally a Tangram puzzle task.

Measures

Body Movement

The program *DeepLabCut* (Mathis, 2018) was used to analyze the body position of both mother and child through video recordings. Upper body positions were hand-labeled by trained research staff on 25 randomly selected frames and a machine-learning approach was used to predict body position and a measure of reliability throughout the rest of the video (Mathis, 2018). Labels were placed on 14 individual body parts (i.e., forehead, left elbow) and generated an x- and y-axis position over time. Labels were chosen based on standards set by Koul and colleagues (2023). Specifically, markers were placed on the cheeks, nose, collarbone, shoulders, elbows, palms, and fingertips. Due to restrictions with the camera angles, only upper body positions were labeled. This process was completed for mother and child from two camera angles, and the machine-learning prediction with the highest reliability was chosen for everyone. Data that had missing values for more than one-third of the time series were removed, and the resulting datasets were interpolated and resampled to 5Hz. Each body marker's data was smoothed with a moving average then transformed into a measure of velocity by calculating the 1st derivative of the XY Euclidean distance. This measure of velocity calculates gross body movement irrespective of direction. Finally, each body marker was averaged to calculate gross body velocity for both parent and child and smoothed with another moving window.

Respiratory Sinus Arrythmia

Participants were outfitted with noninvasive wireless ECG electrodes connected to a *BIOPAC* belt to monitor heart rate throughout the phases of the study. The belt wirelessly transmitted data at 1KHz to a *BIOPAC* MP160 system. Electrodes were placed on the chest and stomach following *BIOPAC* procedure: ground and VIN+ electrodes were on the participants stomach above the belly button on the left and right side, while VIN- electrodes were placed below the left collarbone (BIOPAC, Santa Barbara, CA, USA). Data was recorded using *BIOPAC*'s software AcqKnowledge. Trained research assistants segmented the ECG data using CardioPeak+Segmenter from the duration of the visit into smaller sections synchronized in time. The removal of artifacts was then completed offline using CardioEdit software to add, divide, or average midbeats (Brain Body Center, University of Illinois at Chicago). Following data cleaning, IBIs were estimated, and a bandpass filter was applied to isolate variance, then resampled to 5Hz (Koul et al., 2023). Respiration was approximated and used to filter out respiratory frequency in the ECG data to create an approximate measure of RSA, which was then made continuous by taking the natural log of the variance within a 15s sliding window. (Abney et al., 2021).

Tangram Task

During the Tangram puzzle task, mothers and children were asked to match the shapes on set cards (*i.e., Penguin, Castle, Radish*) using small wooden shapes (Nguyen et al., 2021). Participants were asked to work either individually or cooperatively in 2-minute increments. During each condition, participants were given two developmentally advanced puzzles and asked to finish the first before starting the second. The puzzles were randomly generated prior to the start of the visit. After a one-minute break, participants would be provided with new puzzles and switch conditions. This continued until each dyad completed both two individual and two cooperative puzzles. Individual or Cooperative puzzle conditions were randomized across dyads prior to the start of the visit. During the individual condition, a physical divider was placed between the parent and child to block line-of-sight and prevent coworking. During the cooperative condition, only one set of puzzles and associated pieces were provided to the pair. After two minutes of puzzling, a timer sounded, and participants were scored based on the number of puzzles completed in each condition (0-2).

Analytic Plan

Statistical analyses were conducted using RStudio and MATLAB. ANOVAs were conducted to test associations between tangram performance and demographic variables. To evaluate differences in the cooperative and individual conditions, RSA and movement data were segmented into distinct datasets by condition. Analyses related to task performance are further segmented to highlight differences between mothers and their children. All analyses were calculated and compared for each 2-minute segment in the dyad.

Surrogate analyses were conducted to determine if physiological synchrony occurs at all levels above and beyond random pairs of dyads (Hypotheses 1a and 1b). To prepare the data, time series for both RSA and IMS were resampled to 5Hz. The autocorrelation of each time series was removed to ensure that there are no spurious effects. The resulting time series were submitted to cross-correlation and the lag0 coefficient was estimated to index empirical synchrony. To determine that synchrony exists beyond random chance, two new pseudosynchrony datasets were generated by randomly shuffling time and randomizing surrogate pairs of dyads that were not assessed together. Finally, Kolmogorov-Smirnov (K-S) tests were conducted to determine whether the empirical dataset differs from both the shuffle and surrogate datasets (Abney, 2021). We expect that the empirical dataset will significantly differ from both shuffle and surrogate during the cooperative condition, but not the individual condition.

To test the hypothesis that positive RSA and movement synchrony predict greater task performance in the Tangram task (Hypotheses 2a and 2b), linear mixed-effects models were used to predict Tangram performance (0-2) with condition (cooperative vs. individual) and synchrony (either RSA or Movement) as fixed factors and with random slopes for both condition and synchrony. To test the hypothesis that both types of synchrony will contribute unique variance to the prediction of Tangram performance (Hypothesis 3), both types of synchrony were introduced in a stepwise model procedure by calculating the change in R^2 (Nakagawa & Schielzeth, 2012). We expect that positive RSA and movement synchrony will be significantly associated with Tangram performance, and that each measure of synchrony will explain unique variance to the prediction of performance scores.

Table 1

Sample Racial Demographics

Race/Ethnicity	Mother	Child
% White	33	23
% Black	33	28
%Hispanic	26	23
%Asian	8	21
%Biracial	0	5

Table 2
Sample Yearly Income

Yearly Income	% of participants
$0-$19,999	0
$20,000-$39,999	11
$40,000-$59,999	15
$60,000-$79,999	15
$80,000-$99,999	23
Over $100,000	36

Table 3
Sample Percentage of Mother Age

Age (years)	% of Mothers
20-30	5
30-40	56
40-50	33
Over 50	3
Unanswered	3

Table 4
Sample Percentage of Child Age

Age (years)	% of Children
5	26
6	38
7	36

CHAPTER 3

RESULTS

Task Performance and Demographic Variables

Table 1 Multiple one-way ANOVAs were conducted to explore the relationship between Tangram task performance and demographic variables for each of the four puzzles. An a priori power analysis was conducted in G*Power to determine the ideal sample size to find a medium effect with the parameters (f = 0.25, a = 0.05, *# of groups* = 2) (Erdfelder et al., 1996). The total sample size required to find a medium effect is n = 210, indicating that we are not sufficiently powered to explore the relationship between demographic variables and task performance.

No demographic variables were significantly associated with child performance. Parent tangram scores during the final puzzle were significantly associated with parent race/ethnicity ($F(3, 35) = 4.21$, $p = 0.01$), and family income ($F(4,34) = 3.34$, $p = 0.02$), as seen in Tables 5 and 6. There were no significant results for any other puzzles.

Table 5
Race and Tangram Performance ANOVA

Individual	Puzzle Number	DF	F-Statistic	p-value
Parent	1	3	1.71	0.18
Parent	2	3	0.45	0.72
Parent	3	3	0.31	0.82
Parent	4	3	4.21	0.01**
Child	1	4	0.77	0.55
Child	2	4	1.92	0.13
Child	3	4	0.40	0.81
Child	4	4	1.42	0.25

Table 6

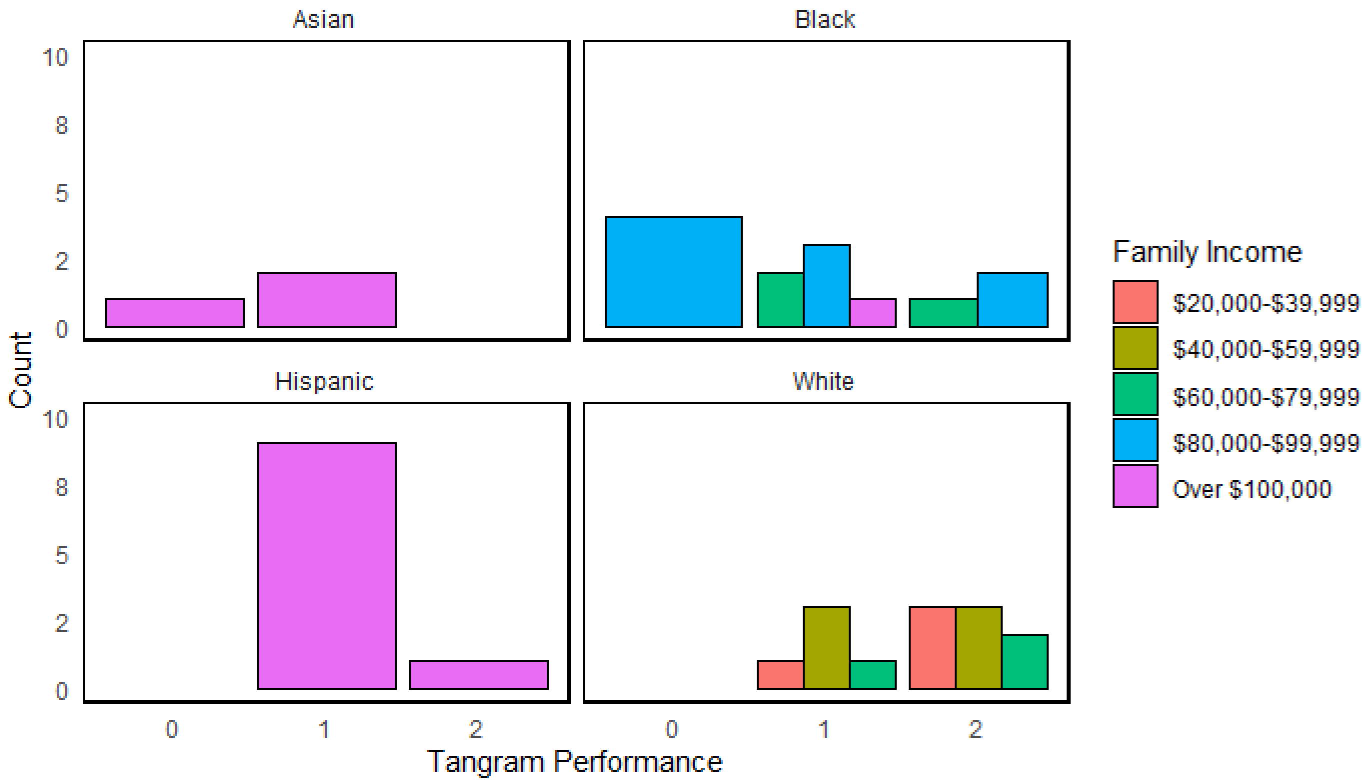
Income and Tangram Performance ANOVA

Puzzle Number	DF	F-Statistic	p-value
1	4	1.53	0.22
2	4	0.34	0.85
3	4	0.32	0.86
4	4	3.34	0.02*

A two-way ANOVA explored how the combination of parent race and family income predicted Tangram performance scores. In the combined model, parent race no longer significantly predicted performance $F(3, 31) = 0.58$, $p = 0.63$, while family income remained a significant predictor $F(4, 31) = 3.21$, $p = 0.02$, such that a higher family income group predicted greater performance. Figure 1 visualizes the number of parents in each income group and their performance scores and suggests this relationship may be due to sample size. A final two-way ANOVA evaluated whether the relationship between family income and task performance during the final puzzle could be explained by starting condition (cooperative or individual). In this model, family income similarly predicted performance $F(4, 31) = 3.24$, $p = 0.02$, while starting condition did not $F(1, 31) = 0.05$, $p = 0.82$.

Figure 1

Fourth puzzle Tangram performance scores by income and race/ethnicity



Quantifying Synchrony

Interpersonal movement synchrony and RSA synchrony were each derived from time series during each puzzle for both parent and child. Figure 2 displays the time series of an example participant. To create a measure of synchrony, cross correlation coefficients (CCFs) were calculated between parent and child. To account for the fact that time series are not independent over time, each time series for mother and children was first prewhitened. Prewhitening each time series before calculating CCF removes the autocorrelation of each time series through trends that naturally occur over time while showing which time lags of one time series are predictive of the other. Prewhitening then helps avoid spurious and random correlations. Figures 3 and 4 depict movement and RSA CCFs before and after removing the autocorrelation, with the threshold for which a correlation is significantly different from 0. Lag-0 CCFs were used as the measure of synchrony between parent and child during each puzzle following standards set by previous research, and after confirming that lag-0 often crossed the significance threshold. Positive CCF values are associated with positive synchrony, while negative values are associated with negative synchrony. The data was segmented by starting condition to accurately determine whether a puzzle represented a cooperative or individual. Figures 5-8 portray the CCFs of each dyad at each puzzle.

Preliminary comparison of means t-tests were conducted to examine group differences in movement and RSA CCFs in the individual and cooperative conditions. Neither movement (t = 0.83, $p > 0.05$) nor RSA (t = -0.01, $p > 0.05$) CCFS were significantly different in the individual and starting conditions.

Table 7
Adjusted Sample Sizes for Starting Condition

Starting Condition	N
Individual	23
Cooperative	16

Figure 2

Time series of movement and RSA for example parent and child during each puzzle.

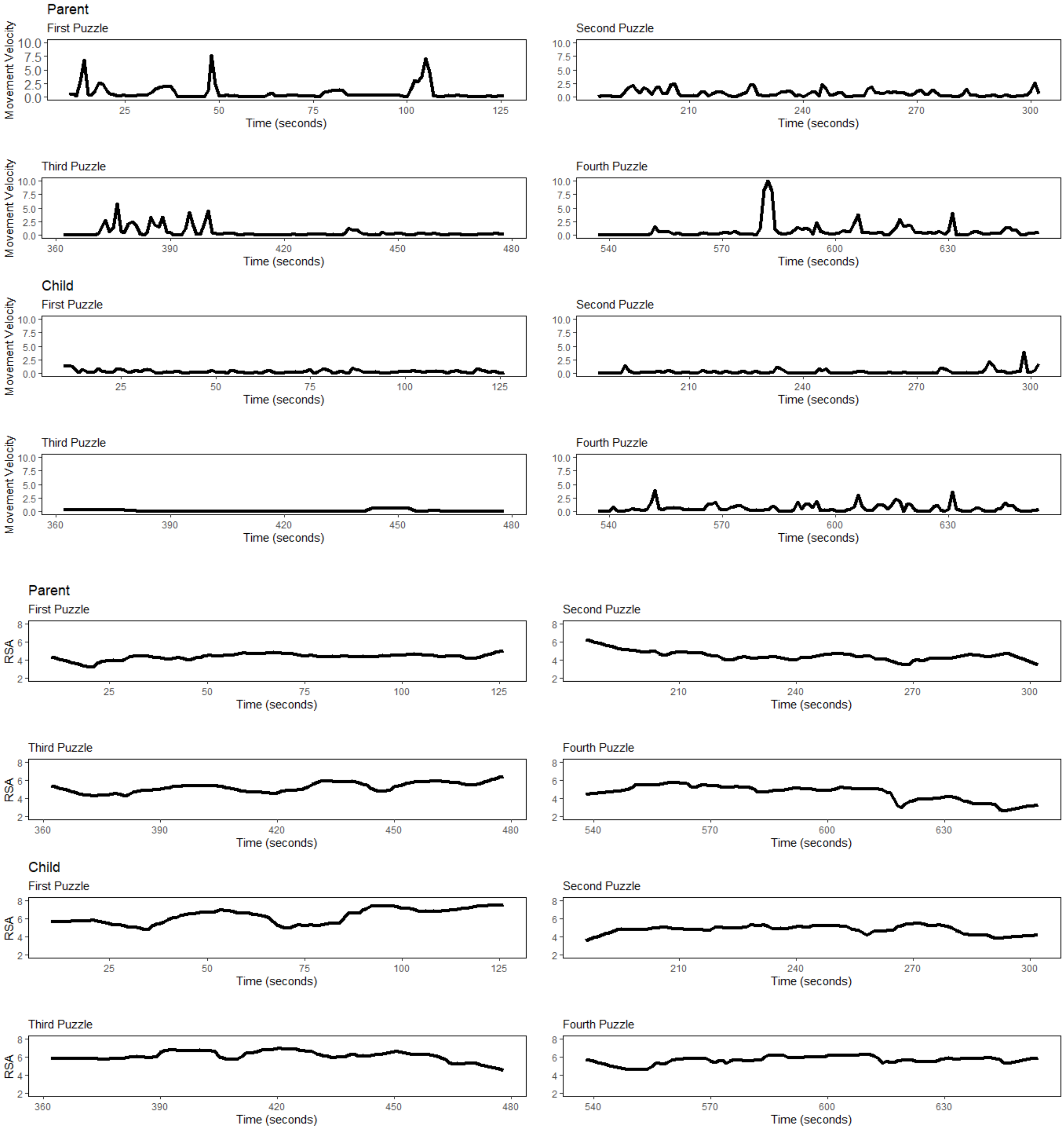


Figure 3

Movement Velocity CCFs before and after prewhitening

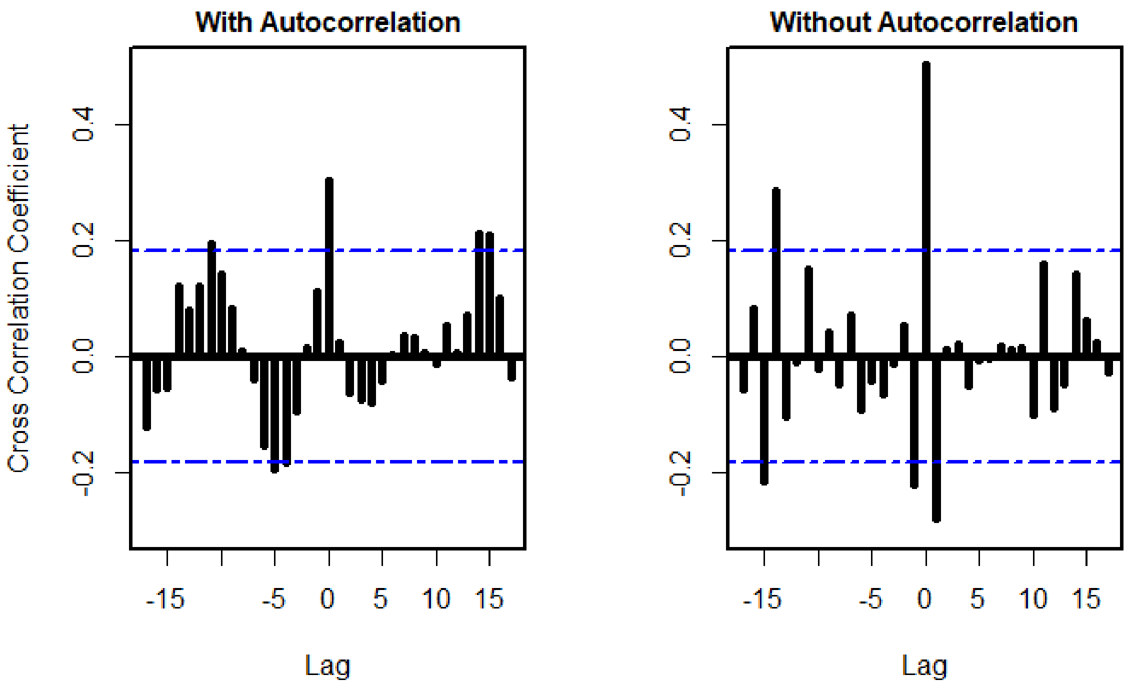


Figure 4

RSA CCFs before and after prewhitening

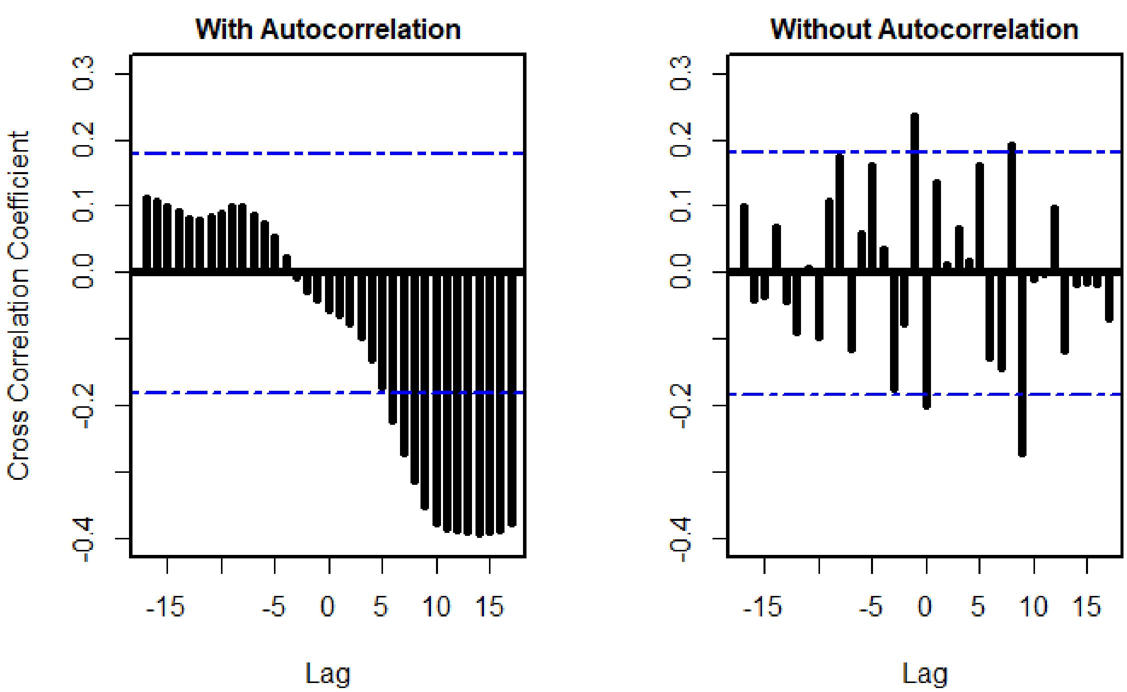


Figure 5

Movement CCFs for each dyad in the cooperative starting condition

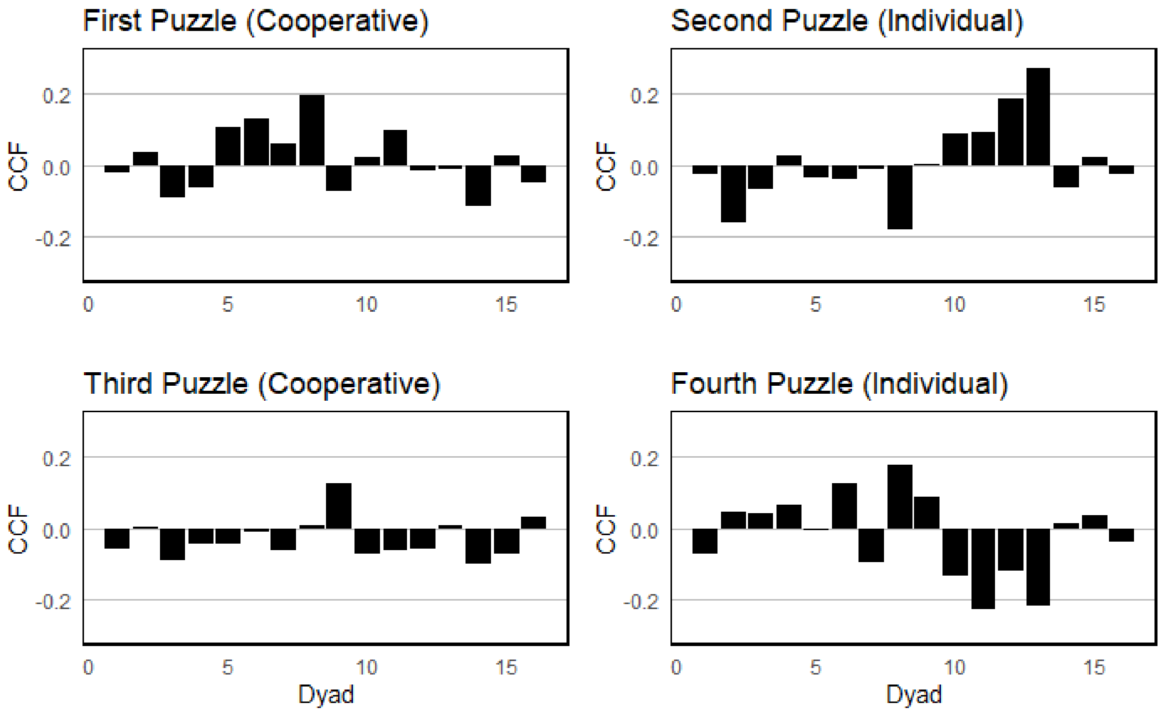


Figure 6

RSA CCFs for each dyad in the cooperative starting condition

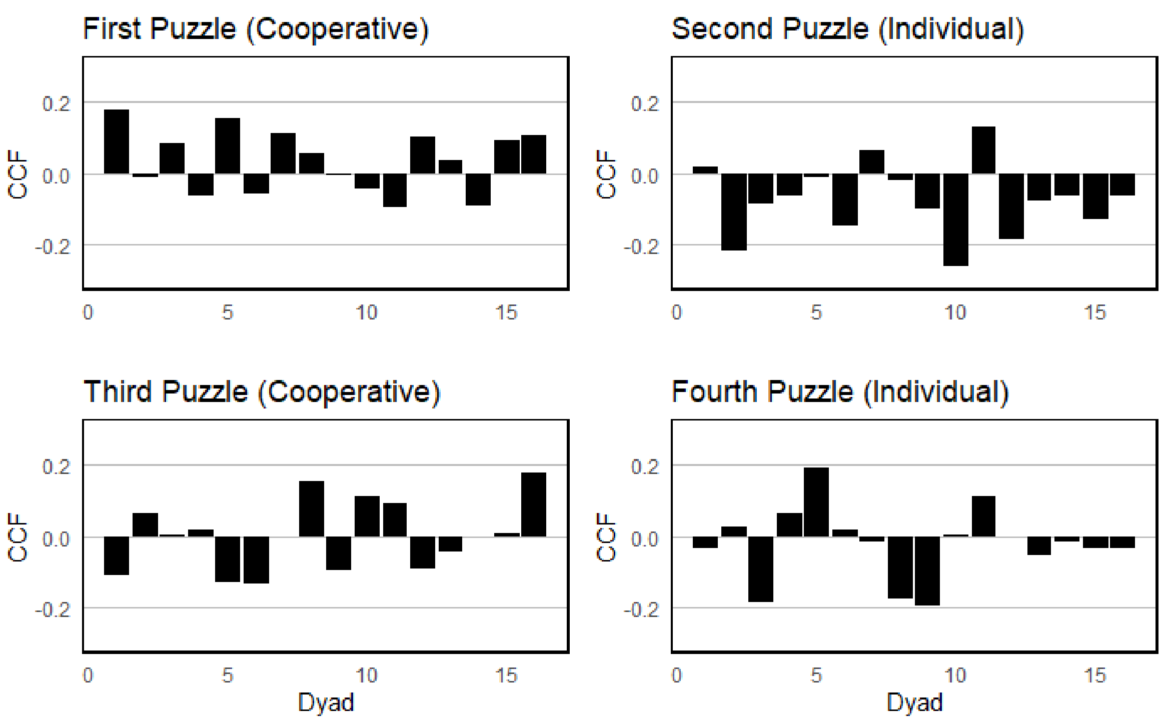


Figure 7

Adjusted Sample Sizes for Starting Condition

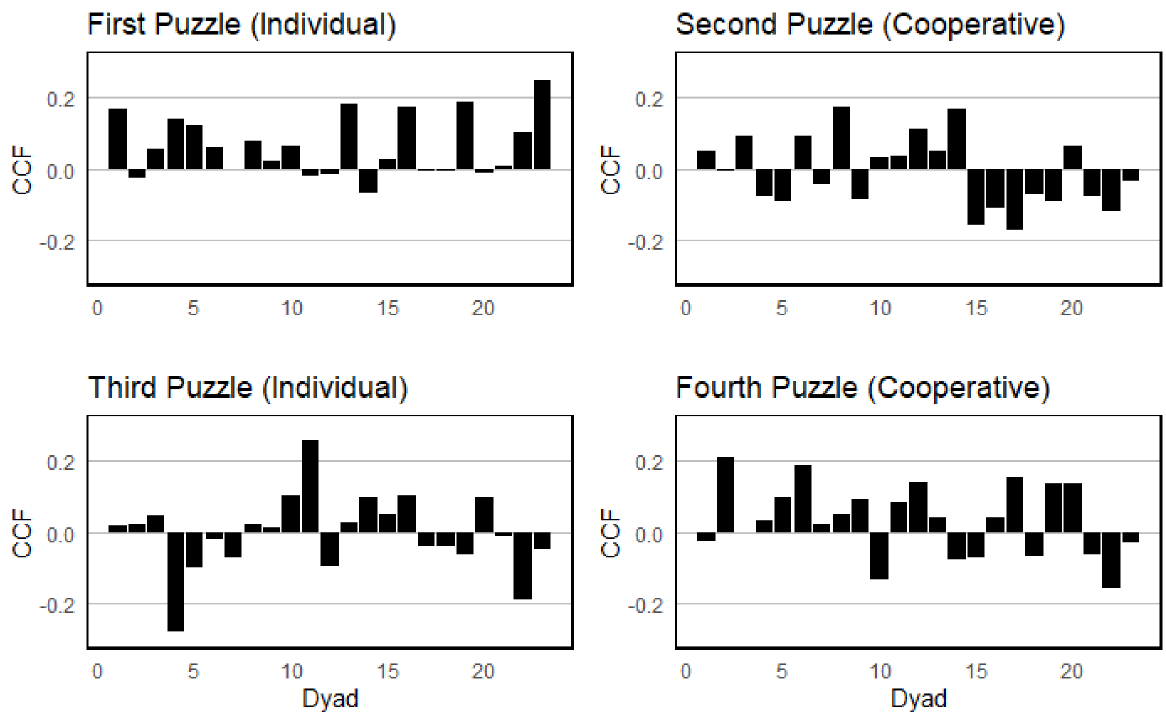
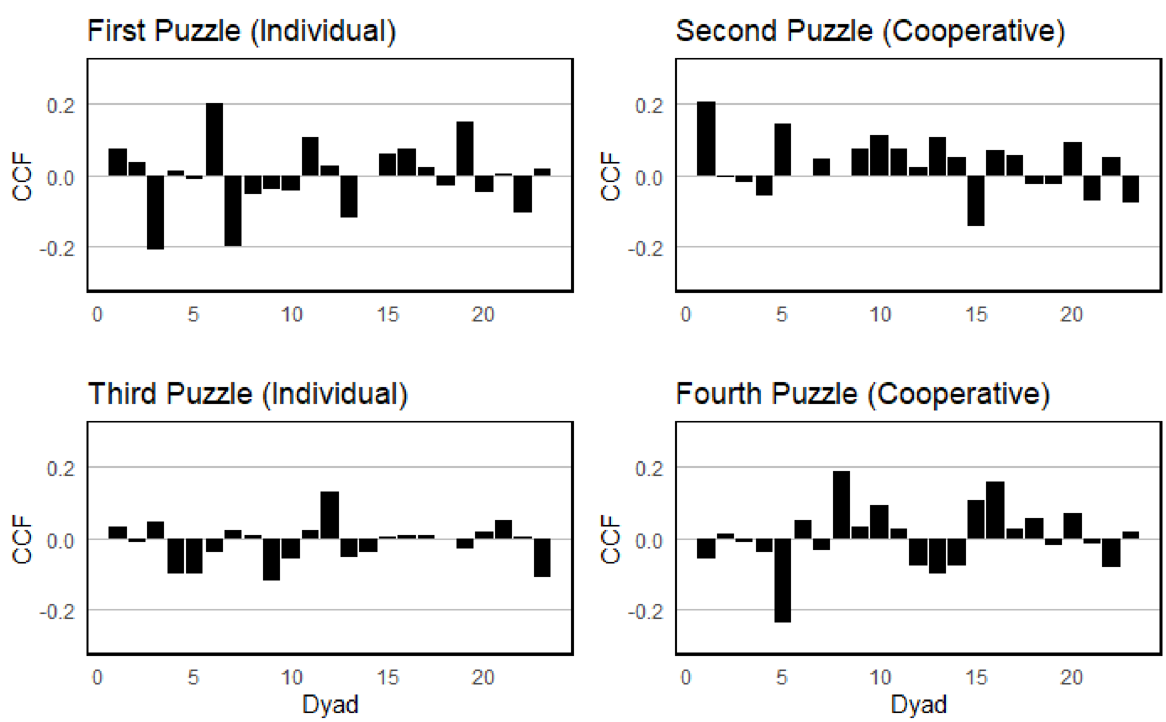


Figure 8

Adjusted Sample Sizes for Starting Condition



Verifying Synchrony

To test the hypotheses that interpersonal movement synchrony and RSA synchrony emerged during a cooperative puzzle task, and not during an individual puzzle task Kolmogorov-Smirnov (K-S) tests were conducted to compare the original CCFs with the randomly generated shuffle and surrogate CCFs. We expect that the K-S tests for any puzzle that mother and child worked on cooperatively (puzzles 1 and 3 for the cooperative starting condition; puzzles 2 and 4 for individual) will be significantly different while puzzles that mother and child worked on individually will not.

Table 8 shows a total of 16 K-S tests compared the empirical and shuffle datasets to test whether synchrony emerges above and beyond random coincidence. For movement, there were no significant differences in any of the four puzzles, regardless of starting condition. For RSA, the fourth puzzle in the cooperative starting condition was significant ($D = 0.81$, $p < 0.00$). However, as an individual puzzle and with no other significant RSA results, we do not have sufficient evidence to support the claim that movement or RSA synchrony emerged beyond random coincidence.

Table 9 shows a total of 16 K-S tests compared the empirical and surrogate datasets to test whether synchrony emerges from mother and child pairings, as opposed to other random factors. For movement, there were no significant differences in any of the four puzzles, regardless of starting condition. For RSA, the second puzzle in the cooperative starting condition was significantly different ($D = 0.4$, $p = 0.02$). However, as an individual puzzle and with no other significant RSA results, we do not have sufficient evidence to support the claim that movement or RSA synchrony emerged from mother and child dyads.

Table 8
Shuffle K-S Tests

Synchrony Type	Puzzle Number	Starting Condition	D	p-value
Movement	1	Cooperative	0.188	0.95
Movement	2	Cooperative	0.25	0.72
Movement	3	Cooperative	0.38	0.21
Movement	4	Cooperative	0.31	0.43
Movement	1	Individual	0.26	0.42
Movement	2	Individual	0.26	0.42
Movement	3	Individual	0.39	0.06
Movement	4	Individual	0.30	0.24
RSA	1	Cooperative	0.31	0.43
RSA	2	Cooperative	0.31	0.43
RSA	3	Cooperative	0.36	0.21
RSA	4	Cooperative	0.81	0.00***
RSA	1	Individual	0.26	0.42
RSA	2	Individual	0.39	0.06
RSA	3	Individual	0.26	0.42
RSA	4	Individual	0.35	0.12

Table 9
Surrogate K-S Tests

Synchrony Type	Puzzle Number	Starting Condition	D	p-value
Movement	1	Cooperative	0.16	0.87
Movement	2	Cooperative	0.15	0.90
Movement	3	Cooperative	0.31	0.12
Movement	4	Cooperative	0.22	0.49
Movement	1	Individual	0.14	0.81
Movement	2	Individual	0.31	0.38
Movement	3	Individual	0.15	0.75
Movement	4	Individual	0.10	0.98
RSA	1	Cooperative	0.19	0.69
RSA	2	Cooperative	0.4	0.02*
RSA	3	Cooperative	0.17	0.80
RSA	4	Cooperative	0.26	0.30
RSA	1	Individual	0.32	0.27
RSA	2	Individual	0.15	0.72
RSA	3	Individual	0.11	0.95
RSA	4	Individual	0.27	0.11

Synchrony and Task Performance

Linear mixed effects models were used to test the hypothesis that movement and RSA synchrony predict task performance in a dyadic tangram task (Hypotheses 2a and 2b). A priori power analysis was conducted in G*Power to determine the required sample size to find a medium effect with the parameters ($f = 0.25$, $a = 0.05$, *# of groups* = 2, *# of measurements* = 3) (Erdfelder et al., 1996). The power analysis indicated that a total sample size of $n = 72$ is required to find a medium effect of the relationship between CCFs and task performance. Data were split by individual to account for scores in the individual condition. Scores for the cooperative condition and CCFs are shared between parent and child. All linear mixed effects models predicted performance (0-2) with synchrony CCFs (Movement or RSA) and condition (Individual or Cooperative) as fixed effects, and synchrony CCFs and dyad as random effects. The distribution of Tangram scores is displayed in Figures 9 and 10.

The linear mixed effects model testing the association between tangram performance and movement for parents found no significant effect of condition (*Estimate* = 0.07, *SE* = 0.08, $p > 0.05$) or interpersonal movement synchrony (*Estimate* = -0.30, *SE* = 0.48, $p > 0.5$), suggesting that neither puzzle condition nor movement synchrony are predictive of tangram performance.

The linear mixed effects model testing the association between tangram performance and movement for children found no significant effect of interpersonal movement synchrony (*Estimate* = 0.39, *SE* = 0.45, $p > 0.5$), suggesting that it is not predictive of Tangram performance. There was a significant effect of condition (*Estimate* = -0.67, *SE* = 0.08, $p < 0.01$), suggesting that children were more likely to score higher on the Tangram task when working with their mother.

The linear mixed effects model testing the association between tangram performance and RSA for parents found no significant effect of condition (*Estimate* = 0.09, *SE* = 0.08, $p > 0.05$) or RSA synchrony (*Estimate* = 0.60, *SE* = 0.45, $p > 0.05$), suggesting that neither puzzle condition nor movement synchrony are predictive of tangram performance.

The linear mixed effects model testing the association between tangram performance and RSA for children found no significant effect of RSA synchrony (*Estimate* = 0.34, *SE* = 0.43, $p > 0.05$), suggesting that it is not predictive of Tangram performance. There was a significant effect of condition (*Estimate* = -0.67, *SE* = 0.08, $p < 0.01$), suggesting that children were more likely to score higher on the Tangram task when working with their mother.

Stepwise linear mixed effects models were used to test the exploratory hypothesis that RSA and movement synchrony will contribute unique variance to the prediction of tangram performance (Hypothesis 3). The variables Condition, RSA CCF, and Movement CCF were added to the model in order of smallest p-value for both parent and child. For mothers, the variables were loaded in the order 1) RSA CCF, 2) Movement CCF, 3) Condition. For children, the variables were loaded in the order 1) Condition, 2) RSA CCF, 3) Movement CCF.

For mothers, RSA did not explain a significant amount of the variance in Tangram performance scores (*Estimate* = 0.62, *SE* = 0.40, $p > 0.05$, $R^2 = 0.11$). While the addition of both condition (*Estimate* = 0.08, *SE* = 0.09, $p > 0.05$, $R^2 = 0.16$) and movement (*Estimate* = -0.16, *SE* = 0.46, $p > 0.05$, $R^2 = 0.17$) contributed more variance to task performance, it was not significant.

For children, condition explained a significant amount of variance in Tangram performance scores (*Estimate* = -0.65, *SE* = 0.08, $p < 0.01$, $R^2 = 0.26$). Neither the addition of

RSA (*Estimate* = 0.48, *SE* = 0.38, $p > 0.05$, $R^2 = 0.26$) nor movement (*Estimate* = 0.37, *SE* = 0.44, $p > 0.05$, $R^2 = 0.27$) contributed any additional significant variance to the prediction of tangram scores.

Figure 9

Boxplot of Movement CCFs and Tangram Performance

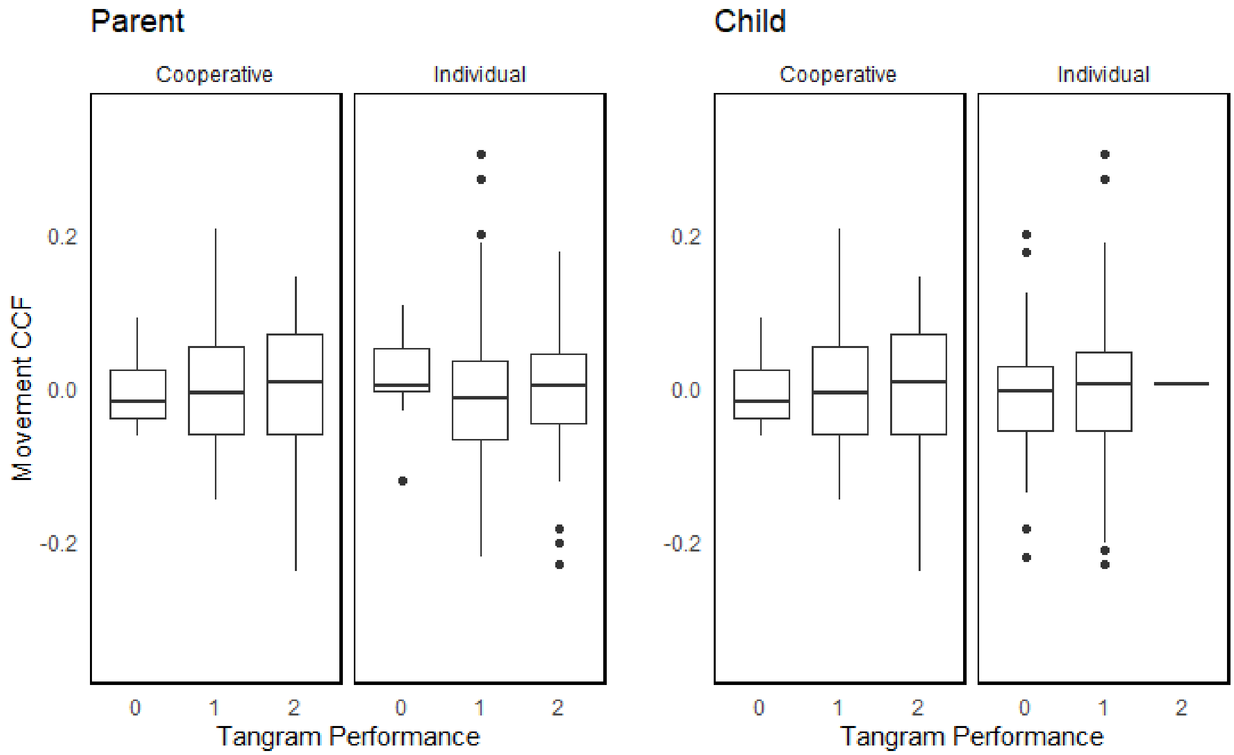
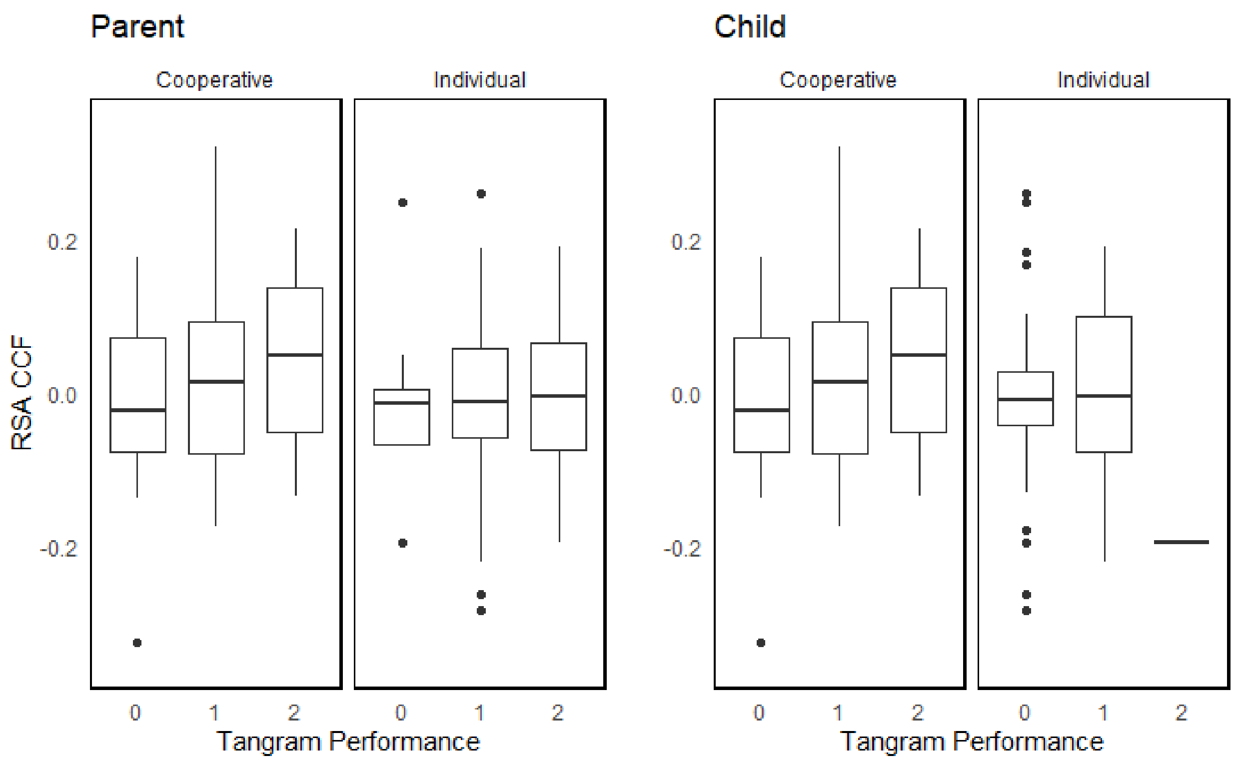


Figure 10

Boxplot of RSA CCFs and Tangram Performance



CHAPTER 4
DISCUSSION

Task Performance and Demographic Variables

Fundamentally, the study of dynamical systems in families should require an understanding of the environmental context of each family. As such, demographic variables are important in understanding the interaction between parents, children, and their environments. In the current study, we found associations between tangram performance, parent's race/ethnicity, and family income during a single puzzle, regardless of starting condition. It should be noted, however, that there was not sufficient power to find even a medium effect size of demographic variables on tangram task performance.

Previous literature on the relationship between income and child task performance in puzzles has not displayed mixed results. In a study on mother-child shape-match puzzle, which is like the Tangram puzzle, Robinson and colleagues found that income was not a predictor of performance in low-income dyads (Robinson et al., 2009). However, future research should consider income alongside educational ability, as well as familiarity with research studies. The level of stress in the lab could influence physiological synchrony. I believe that the cause of this effect for this single puzzle had more to do with a disproportionate sample than an interaction between income and parent's puzzle task performance. The number of participants who earned more than $100k in the sample was half, although interestingly all the participants with a high income were also Hispanic. It is due to this fact that neither income nor race, which was less predictive, were included in any subsequent analyses. However, the fact that income persisted above and beyond both race and condition should not be ignored, and future studies should account for familial income when examining puzzle task performance, potentially with a more robust scale that extends beyond 100k.

While race and ethnicity did not explain significantly more variance in performance scores than income, there is still evidence in previous literature to suggest that there is a relationship worth considering. Pham and her colleagues examined ethnic differences in mother's and children's responses to child's performance in a puzzle task, finding that children how negatively children responded to the challenge of the task (Pham et al., 2023). Additionally, there is an interesting interaction between parent ethnicity, gender, and mother's guidance during a puzzle (Levine et al., 2012; Sanagavarapu, 2012). However, this relationship has only be studied in small groups, and should be further explored, potentially with both mother- and father-dyads to test for potential gender effects for parents. Finally, future studies should seek to delineate between race and ethnicity to better understand unique variance provided by each.

Emergence of Synchrony

I hypothesized that both IMS and RSA synchrony would emerge during the tangram task when mother and child worked cooperatively, and not when they worked individually (1a and 1b). There were no significant differences in movement or RSA CCFs when comparing the cooperative and individual conditions. Additionally, there were no instances that IMS synchrony emerged, regardless of condition. While there were two instances of RSA synchrony emerging, they each occurred during an individual puzzle, contradicting the hypothesis. As such, I am unable to confirm that either IMS or RSA synchrony emerged during the Tangram task. As a result, all subsequent results, regardless of their outcome or significance, cannot be said to have occurred above and beyond random chance.

In the case of the two significant effects we found, there are four possibilities for what may have occurred that should be considered in future versions of the study. First, it could be possible that RSA synchrony between mothers and children can emerge without visual or physical contact, which is distinct from IMS (Koul et al., 2023). This could also be a delayed effect of RSA synchrony from an earlier, cooperative, part of the task. Recent research by Armstrong-Carter et al. (2021) found that parent RSA synchrony was positively associated with children's RSA 30 seconds later, and children's RSA was negatively associated with parent's RSA 30 seconds later (Armstrong-Carter et al., 2021). By examining and comparing RSA at different time lags, we may better understand its impact on task performance. Second, it is possible that there is something inherent about the tangram puzzle task that influences mothers and children. This feels less likely due to the infrequent significant results. Third, it is possible that there are different effects for positive and negative measures of synchrony. Future studies should consider separating synchrony by valence before running analysis. Finally, it is possible that these results are due to a small sample size / random chance itself.

Synchrony, Task Performance, Problem Solving

I hypothesized that positive IMS and RSA synchrony would positively predict tangram performance scores (2a and 2b). There were no instances in which either IMS or RSA synchrony predicted Tangram task performance for either parent or child. Additionally, power analysis indicated that a much larger sample size is necessary to find even a medium effect. As such, we have no evidence that there is a relationship between IMS and RSA synchrony and task performance. Additionally, I hypothesized that IMS and RSA synchrony would each contribute unique variance to the prediction of task performance (3). As there was no variance in task performance explained by IMS or RSA synchrony, this final hypothesis was demonstrated to be false.

Although these results cannot be said to have occurred greater than random chance, there are nonetheless interesting implications of these negative results. I suggest two possibilities for these results that should be considered in future research. First, it is possible that lag-0 movement and RSA synchrony is simply not predictive of task performance in mother-child dyads. This study focused on two types of synchronies previously unexplored in the tangram task to paint a more complete picture of the behavioral and physiological processes that go into cooperative tasks beyond neural synchrony in father-child dyads and postural sway synchrony in child-child dyads (Nguyen et al., 2021; Vink et al., 2017). We would still expect that in this sample, those previously established measures would predict task performance, and neural synchrony especially has been found to be functionally distinct from ANS synchrony (Reindl et al., 2022). Our results could indicate that there is a functional difference in the roles of IMS and RSA synchrony that is less pronounced during cooperative tasks. Alternatively, these differences may be explained by the differences between mother-child dyads and dyads explored in previous research. The context of the relationship between fathers and their children has the potential to change the results as a different part of the system. For RSA, Lunkenheimer et al. suggested that mothers respond to children’s regulatory ability, while fathers are more influenced by the immediate behavioral context (Lunkenheimer et al., 2021). Additionally, fathers are more affected by positive affect and playful interactions (Bureau et al., 2021), which suggests they may have different approaches that should be compared to mother-child dyads, or mother-father-child triadic tasks.

Second, it is possible that the significant effect of condition on children's task performance scores is overpowering and obscuring the relationship between synchrony and task performance. Children performed better at the task when they were working with their parents in the cooperative condition. This is to be expected, the task is designed to be challenging primarily for children, and they should expect to benefit from the assistance of their mother. The ease of the puzzle could also extend to the lack of significant results for the parents. Perhaps a more complicated or challenging puzzle, or a puzzle with distinct parts for the parent and child to solve together would be a better fit. Alternatively, the large degree of variation in parent-child puzzle play at home may suggest that the more familiar simple puzzles are best as they capture the most naturalistic parent-child interactions (Pochinki et al., 2021). However, since neural synchrony still emerged during the tangram task, any changes to puzzles should be heavily considered and tested first. (Nguyen et al., 2021). Regardless of the reasoning, there is no evidence to suggest that either IMS or RSA synchrony contributes to the success of the tangram task.

Limitations and Future Directions

This study was primarily limited by the diminished sample size and cleanliness of the data. Of the sample, less than half of the participants had usable data, which was not enough to sufficiently power this study. The main culprit for the lowered sample size was the inclusion of movement data. While there were some participants removed for their lack of RSA data, the number was well within expected standards. Movement data was calculated using DeepLabCut, which had trouble continually depicting mother and child for a few reasons. First, the task was not originally designed to track movement, but instead record mother-child interaction for behavioral coding. Due to this, there was a table continually blocking the participants lower body, and a clear view of the upper body was often obscured by the basket of puzzle pieces, or the barrier used to separate mother and child during the individual task. This made individual body parts, especially the upper extremities, inaccurate and occasionally unusable. Future versions of this study should attempt using set full-body camera positions for both parent and child, with multiple camera angles. Additionally, puzzles pieces should be provided directly on the table, rather than in a large basket.

The lighting in the room also created some problems, specifically for participants with darker skin tones. In a few cases, the overhead lighting cast a shadow over the participants' face and body that made it impossible for research to accurately label body parts, lowering the accuracy of movement data. This issue can be easily rectified in future studies by placing a light source behind the camera, instead of over the participant. Additionally, the use of other movement data collection methods, like OpenPose, can automatically detect body position without the time-consuming effort needed to label each body part for multiple body parts and multiple people. Alternatively, the use of accelerometers during the puzzle task could eliminate the need for video-recorded movement altogether.

Participants task performance scores could also have been impacted by fatigue, given that the Tangram was always the last task of a long visit with a purposefully stressful component. By the time we reached the tangram task, many children were uncomfortable with the brain and heart rate monitors and were eager to finish the study. Furthermore, the number of puzzles dyads completed in each condition was small, which could impact analysis. Future research should focus primarily on the tangram task and increase the number of puzzles to complete in each condition.

Given the findings of previous research, future studies should place a stronger emphasis on including neural synchrony as an additional modality during the tangram task. As noted previously, there is also some promise in exploring additional time-lags for RSA during the task. Future studies should also strive to better operationalize and understand the impact of income and race/ethnicity on mother-child behavioral and physiological synchrony. Finally, future research should consider examining loosely coupled dyads rather than those that are strongly synchronized. In some tasks, stronger interpersonal synchrony is less predictive than weak synchrony (loose coupling), suggesting the importance of coordination above synchronization (Abney et al., 2014; Vink et al., 2017). Future studies should consider personalizing analyses to the context of task constraints, dyads, and type of synchrony.

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