Biological basis of temperament: respiratory sinus arrhythmia and inhibitory control across childhood

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Respiratory Sinus Arrhythmia and Inhibitory Control across Childhood

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Abstract

Temperamental inhibitory control is a foundational capacity for children's social, emotional, and behavioral development. Even though temperament is suggested to have a biological basis, the physiological indicators of inhibitory control remain unclear amid mixed empirical results. In this study, we leveraged a multi-cohort longitudinal design to examine resting RSA as a physiological correlate of inhibitory control across the early and middle childhood years. Data was collected annually across four time points from cohorts of 4- (n = 150, M_{age} = 4.53; SD = .30; 49.7% female) and 8- (n = 150; M_{age} = 8.53; SD = .29; 49.7% female) year-old children and their caregivers. There were weak, albeit significant, associations between resting RSA and caregiver-reported inhibitory control in middle childhood but not in early childhood. A stronger association was found for older children when latent trait assessments of RSA and inhibitory control were derived from commonalities across the four annual assessments. We conclude that using repeated measures to extract latent trait scores increases power to detect potential physiological indicators of temperament.

Keywords: respiratory sinus arrhythmia; inhibitory control, early childhood, middle childhood

Public Significance Statement:

-In the current study we examined resting RSA as a biological correlate of temperamental inhibitory control with a multi-cohort, 4-year longitudinal design across early and middle childhood.

-The analyses examining associations between resting RSA and inhibitory control across the latent trait models (derived from four repeated measures) showed significant associations between resting RSA and inhibitory control in middle childhood but not in early childhood.

-Results indicated that the biological correlates of temperamental inhibitory control might become more crystalized in middle childhood and showed that the use of repeated measures to extract latent trait scores would increases power to detect potential physiological indicators of temperamental inhibitory control.

Biological Basis of Temperament:

Respiratory Sinus Arrhythmia and Inhibitory Control across Childhood

Temperament is conceptualized as individual differences in children's emotional reactivity and self-regulation that emerge early in infancy (Rothbart & Bates, 2006). Empirical evidence mostly suggests stability in temperament throughout infancy and childhood, with past work showing medium to large stability estimates (Bornstein et al., 2019; Pedlow et al., 1993). Due to its early formation and relative consistency, temperament is often considered a central ingredient of personality that informs how children approach and interact with their environment (Kagan et al., 2013). One key element of temperament is inhibitory control, which refers to a child's capacity to suppress a desired—or dominant—response to perform a less desired—or subdominant—response in favor of a more adaptive or socially competent outcome (Kagan et al., 2013; Posner & Rothbart, 2000). Inhibitory control emerges in infancy and develops rapidly from late toddlerhood through preschool and early childhood, and then begins to plateau in middle and late childhood (Diamond, 1990; Rothbart & Bates, 2006; Williams et al., 1999). Research also shows rank-order stability in parent-reported (see Roberts & DelVecchio, 2000) and observational (e.g., Dyson et al., 2012) assessments of child temperamental characteristics, including inhibitory control, with such stability increasing in later childhood as compared to infancy and the preschool years (see Roberts & DelVecchio, 2000; Rothbart & Bates, 2006).

Temperamental inhibitory control is considered a foundational aspect of children's social development, as past studies have linked it to higher social competence (Di Norcia et al., 2015), sympathy (Yavuz et al., 2022a), prosocial behaviors (Rhoades et al., 2009), and moral capacities (Kochanska et al., 1997). Theoretically, inhibitory control is thought to promote children's capacity to suppress selfish responses in order to engage in other-oriented responses, and it can

thus be regarded as key to unlocking children's prosocial potential (Eisenberg et al., 2010). Given that inhibitory control has been implicated in these critical developmental outcomes, researchers have sought to identify its underlying mechanisms, with the ultimate goal of better understanding how inhibitory control arises and which factors can be leveraged to promote it. As detailed in the next section, inhibitory control is theorized to have biologically based correlates, such as resting RSA (Porges, 2011), that reflect its temperamental nature (Kagan, 1998). However, previous empirical studies on this topic have used cross-sectional designs and yielded equivocal results. It is plausible that the point-in-time, snap-shot nature of these studies is not sufficient to capture the temperamental or trait-like nature of inhibitory control and its biological correlates. Therefore, the current study leveraged resting RSA and inhibitory control assessments across early and middle childhood (i.e., ages 4–11) to extract trait-like indicators of these constructs and test their correlation.

The Biological Basis of Temperamental Inhibitory Control

Although most conceptualizations recognize temperament as susceptible to some change over time and as bidirectionally associated with contextual factors, such as parenting (e.g., Kiff et al., 2011), children's temperament is thought to be largely stable and biologically based (Kagan, 1998). Different neurobiological characteristics, including the structure and functioning of the prefrontal cortex and limbic structures, have been reliably linked to temperamental characteristics (MacNeill & Pérez-Edgar, 2019; Whittle et al., 2006). For instance, larger volume of the left orbitofrontal cortex and hippocampus was associated with higher temperamental inhibitory control in middle childhood (Whittle et al., 2008). There is also a well-established amygdala model of temperament (e.g., shyness or behavioural inhibition reflecting amygdala hyperactivity to negative social information; Fox et al., 2008). Numerous physiological

explanations for temperament have also been advanced with some support (e.g., control over one's autonomic reactions corresponding to how strongly they respond to situations and how effectively they can regulate those responses; Porges, 2011). These different approaches jointly suggest that understanding the biological correlates of temperament can offer insights into the mechanisms of temperamental capacities, which may be used to identify, monitor, and promote such capacities in children. Moreover, supplementing traditional measures of temperament (e.g., parent reports or observational assessments) with standardized and highly reliable biological assessments might decrease the risk of bias and increase the clarity of findings across studies (e.g., Buchanan, 2016; Herschell et al., 2020). The present study focused on respiratory sinus arrhythmia (RSA) as a potential biological correlate of inhibitory control.

The central and autonomic nervous systems have long been theorized to provide the basis for behavioural manifestations of inhibitory control (Kagan, 1982; Porges, 1995). Polyvagal theory (PVT; Porges, 1992, 1995, 2011) provides a neurophysiological model for how the autonomic nervous system may have evolved to influence the development of more complex self-regulation and social engagement capacities relevant to inhibitory control. According to PVT, the myelinated vagus nerve, responding to neural signalling from the nucleus ambiguus of the medulla, exerts control over the heart by regulating the sinoatrial node. Effective vagal regulation of the heart is thought to soothe the autonomic nervous system in such a way that facilitates dynamic and socially engaged responses to one's context. Similarly, the neurovisceral integration model (NIM; Thayer et al., 2009) suggests that vagal regulation of the heart permits regulated, inhibitory processes that promote successful and dynamic adaptation to emotionally arousing situational demands (i.e., inhibitory control). In both the PVT and NIM, the vagus nerve is theorized to serve as a physiological brake aiding inhibitory control (Porges, 2011).

Vagal control of the heart is often indexed by RSA—the fluctuations in heart rate during spontaneous breathing—which is also commonly referred to as vagal tone (Riniolo & Porges, 2000). Higher resting RSA (i.e., stronger vagal regulation of the heart) is thought to promote adaptive social capacities, such as inhibitory control, as higher RSA may contribute to a more relaxed autonomic state. In contrast, lower resting RSA (i.e., weaker vagal regulation of the heart) is thought to interfere with effective activation of inhibitory processes (Porges, 1992, 1995, 2011; Thayer et al., 2009). When measured in a resting state in the absence of obvious external stimuli, RSA is thought to reflect children's dispositional tendency or capacity for vagally mediated cardiac regulation (Cui et al., 2015; Porges, 2011). Differences in resting RSA seem to fairly reliably predict outcomes related to children's inhibitory control, such as prosocial behaviours (e.g., Taylor et al., 2015; Zhang & Wang, 2019), self-regulation and executive functioning (Beauchaine, 2015), and behavioural problems (e.g., Hinnant & El-Sheikh, 2013; Zhang et al., 2017); however, as shown in the following section, links between RSA and inhibitory control appear to be more mixed upon a deeper review of the literature.

Associations Between Resting RSA and Inhibitory Control During Early and Middle Childhood

Some theoretically consistent empirical studies support the hypothesized positive association between resting RSA and inhibitory control, while others demonstrate mixed associations (i.e., significant for some children or using some measures but not others) and some find no association. For example, using a cross-sectional design, Giuliano et al. (2018) found that higher resting RSA was correlated with higher inhibitory control as measured by two behavioral tasks (i.e., day/night and shapes stroop) in a sample of 3- to 5-year-olds. Taylor et al. (2015) extended this cross-sectional evidence prospectively during the early childhood years, finding a

positive association between higher resting RSA when children were 3.5 years old and higher effortful control (a measure which included parent-reported inhibitory control) when children were 4.5 years old (albeit not controlling for previous levels of inhibitory control). In contrast, other studies found null associations between resting RSA and inhibitory control in early childhood using cross-sectional (e.g., Kahle et al., 2018; Noten et al., 2019; Scrimin et al., 2018; Utendale et al., 2014; Wilson et al., 2011) and longitudinal designs (e.g., Holochwost et al., 2018; Kahle et al., 2018), in middle childhood using cross-sectional designs (e.g., Zhang & Wang, 2019), as well as in cross-sectional studies that grouped both early and middle childhood together (e.g., Quiñones-Camacho & Davis, 2018). With the exception of Wilson et al. (2011), which utilized parent reports, all other above-noted studies used behavioral observation tasks to examine inhibitory control. However, since studies conducted with behavioral observations showed mixed associations, the inconsistencies in the literature cannot be solely attributed to measurement differences.

There is evidence that the relation between RSA and inhibitory control may be more complex than a straight-forward concurrent association, as past work has revealed moderated or mixed associations. For example, using a cross-sectional design, Sulik et al. (2013) found that 3- to 5-year-olds' resting RSA was positively correlated with inhibitory control when children were higher in shyness, but not when children were lower in shyness. In another cross-sectional study, Scrimin et al. (2020) showed that resting RSA was positively correlated with inhibitory control among 6- to 8-year-olds who were lower but not higher in physical fitness. In another study focusing on a wider range of 8- to 17-year-olds, resting RSA was positively correlated with a questionnaire-based assessment of effortful control but not with performance on the go/no-go task (Chapman et al., 2010).

One possible explanation for these mixed associations is that studies examining RSA and inhibitory control rely disproportionately on cross-sectional or short-term longitudinal designs with little to no developmental scope. Although susceptible to change and environmental influence, temperamental inhibitory control is theorized in part as a relatively stable construct that demonstrates *commonality or consistency across time* (Roberts & DelVecchio, 2000). This temporal consistency is impossible to capture with one-time cross-sectional approaches. Even longitudinal studies may fail to capture the temperamental consistency of inhibitory control if they adopt a traditional longitudinal focus on mean-level patterns or prospective prediction rather than on stability or commonality. In line with this idea, one past study by Li et al. (2017) suggests that accounting for stability or commonality within resting RSA and inhibitory control in line with temperamental theory may yield stronger associations between these constructs. The researchers found that resting RSA was not concurrently related to effortful (including inhibitory) control when children were 2 or 4 years old. However, *stability* in resting RSA across these two time points predicted higher stability in effortful control across the same two time points. These findings suggest that extracting stable, temperamental components from repeated measures of resting RSA and inhibitory control may result in more robust, theory-based operationalizations of these constructs. Correlations between temperamental measures derived from their stability across time points may be more consistent and thus more useful for understanding the physiological correlates of inhibitory control.

Developmental Considerations

It is generally recognized that temperament emerges early and stabilizes with age (Casalin et al., 2012; Bornstein et al., 2019; Putnam et al., 2002). More specifically, temperament is expected to be less stable in infancy through early childhood but to become more crystalized in

middle childhood onward (Martin et al., 2020). Similarly, RSA is expected to stabilize into middle childhood (El-Sheikh, 2005; Gentzler et al., 2012, Hinnant et al., 2011), or even slightly decrease into middle childhood and adolescence (Salomon, 2005). Moreover, some studies suggest that resting RSA becomes more predictive of developmental outcomes in middle childhood as compared to the preschool years (e.g., Beauchaine et al., 2007). Much of the extant research assessing links between resting RSA and inhibitory control has focused on samples in early childhood, showing mixed or null associations. To the best of our knowledge, only three cross-sectional studies have assessed the link between resting RSA and inhibitory control in middle and later childhood, with one showing null associations (Zhang & Wang, 2019), and the remaining two showing some evidence of positive associations between resting RSA and inhibitory control (Chapman et al., 2010; Scrimin et al., 2020). Thus, the existing evidence paints an unclear picture of the resting RSA–inhibitory control link in earlier vs. later childhood. Taking a broader developmental stance to consider the link between resting RSA and inhibitory control *across early and middle childhood* in the same study may offer a better understanding of if and when in development resting RSA relates to inhibitory control.

The Present Study

To address the aforementioned gaps in the literature, we used a multi-cohort longitudinal design (i.e., a younger cohort of 4-year-olds and an older cohort of 8-year-olds, each assessed annually four times from 4 to 7 years of age and 8 to 11 years of age, respectively) to assess the RSA–inhibitory control link across early and middle childhood. Our research aims and hypotheses were three-fold. As a first step, we aimed to replicate previous cross-sectional studies by assessing whether resting RSA was concurrently associated with inhibitory control at each time point. While we theoretically expected positive concurrent links (especially in the older

cohort when both resting RSA and inhibitory control are thought to become more stabilized), our hypotheses at this step remained tentative given the previous mixed literature. As our second and main step, we leveraged our longitudinal design to determine whether a latent trait measure of resting RSA representing what was stable or common across four annual assessments was associated with a latent trait measure of inhibitory control derived in the same manner. As the common information from years of repeated measures should afford a more robust temperamental indicator than any single-time-point measure, we expected resting RSA and inhibitory control to be most strongly and positively correlated at this step. Third and finally, we assessed developmental differences in the aforementioned associations between early (i.e., 4–7 years) and middle childhood (i.e., 8–11 years). Since temperament and underlying RSA are thought to become more consistent with age (see Beauchaine et al., 2007; Bornstein et al., 2019; Pedlow et al., 1993), we expected stronger longitudinally derived associations between trait RSA and trait inhibitory control in the older cohort relative to the younger cohort.

Method

Participants

Participants included 4-year-old (n = 150; M_{age} = 4.53; SD = 0.30; 49.7% female; hereafter referred as the younger cohort) and 8-year-old (n = 150; M_{age} = 8.53; SD = 0.29; 49.7% female; hereafter referred as the older cohort) children and their caregivers (85.3% mothers; 98.7% biological parents; 94.7% married/in domestic partnership) at the initial time of assessment (see Table 1 for descriptive statistics). For both age cohorts, the participants were followed up yearly for 3 consecutive years (i.e., ages 4, 5, 6, and 7 for the younger cohort and ages 8, 9, 10, and 11 for the older cohort). The participants were all fluent in English and were recruited from different community centers or summer events/camps in an ethnically diverse

Canadian city. Consistent with the region from which the sample was drawn (blinded for peer review), participants identified as Western European (25.9%), Asian (26.6%), multiethnic (22.4%), or other (25.1%), and most had a bachelor's degree or higher (79.6%).

Procedure

The Research Ethics Board of the researchers' institution approved the study prior to the commencement of data collection. Families were invited to the laboratory for assessments of inhibitory control and resting RSA for four consecutive time points with one-year intervals in between. Parents were asked to reschedule in the event that children were overly tired, hungry, or ill before a laboratory visit. For each assessment point, informed consent from caregivers and verbal assent from children were obtained, caregivers and children were debriefed, and children received an age-appropriate book upon session completion.

Measures

Inhibitory Control

At all four time points, caregivers rated their child's inhibitory control. In line with theorizing on temperament, they were explicitly asked to consider the usual/general behavior of their child. For the first three waves of the younger cohort, we used 7 items from the Children's Behavior Questionnaire (CBQ; designed for preschool age group; Rothbart et al., 2001). For the final wave of the younger cohort (i.e., age 7) and for all waves of the older cohort (ages 8–11) we used 8 items from the Temperament in Middle Childhood Questionnaire (TMCQ; designed for 7- to 11-year-olds; Simonds & Rothbart, 2004). The use of different scales with different age groups was to ensure the developmental appropriateness of the scales. The scales include overlapping items (e.g., on planning things, being cautious, being able to stop an activity or wait for something) and are generally similar. For both the CBQ and TMCQ, the items were rated on

a 7-point scale (0 = *never* to 6 = *almost always*). The reliability of the scale items was good for each age group across all 4 time points (4-year-olds: α_{T1} = .70, α_{T2} = .74, α_{T3} = .70, α_{T4} = .77; 8-year-olds: α_{T1} = .74, α_{T2} = .72, α_{T3} = .77, α_{T4} = .75).

Resting RSA

Resting RSA data was collected in the laboratory while children watched a 120-second neutral video depicting an aquatic scene. The task did not require the children to talk or move. They were seated comfortably and were instructed to minimize movement during the video. Three adhesive electrodes were attached to the child's right clavicle, and right and left rib cage. The Biopac MP150 data acquisition system and BioNomadix modules (Biopac Systems Inc, RRID:SCR_014829) were used, and the data was sampled at a rate of 2 kHz. AcqKnowledge 4.2 data acquisition software (RRID:SCR_014279) received data from the BioNomadix modules via the MP150. We used Mindware HRV 3.0.21 software (Mindware Technologies, Gahanna, OH, USA) to process and clean the data in 60-second intervals, and to calculate the resting RSA scores. The data was excluded from analyses if more than 20% of an interval required cleaning (rejection rate: 11.2% at T1, 23.9% at T2; 9.3% at T3, and 13.1% at T4). We adjusted the RSA band to 240-1.040 Hz as per recommendations for children under 12 years of age. The mean RSA across the 120-second video was calculated as the final resting RSA score used in this study (see Kiff, 2012 and Pang & Beauchaine, 2013 for similar procedures with similar samples).

Data Analysis Plan

Preliminary analyses were conducted with SPSS 28.0 and single factor longitudinal measurement models were conducted with M*plus* 8.1.8 (Muthén & Muthén, 1998–2017). We first ran descriptive statistics, zero-order correlations, and *t*-tests to examine gender differences for each cohort and each time point. For our first research aim of replicating previous cross-

sectional studies, we examined the concurrent associations between resting RSA and inhibitory control at each of the 4 time points via correlational analyses. For our second and main research aim, we conducted preliminary growth curve analyses of inhibitory control and resting RSA to ensure that subsequent single-factor longitudinal measurement models acknowledged the underlying mean-level patterns and variability in the longitudinal data before we extracted latent traits of resting RSA and inhibitory control. We then ran single-factor longitudinal measurement models as per Geiser (2020) for RSA and inhibitory control. This model creates latent traits using the common information across timepoints/repeated measures. We examined the association between the resulting resting RSA and inhibitory latent traits. Finally, we addressed our third research aim by running the aforementioned correlations and single-factor longitudinal measurement models separately for the younger and older cohorts. We determined adequate model fit with the χ^2 statistic (non-significant), the root mean square error of approximation (RMSEA < .08) and corresponding 90% confidence interval, the comparative fit index (CFI > .90), the Tucker–Lewis index (TLI > .90), and the standardized root mean square residual (SRMR < .09; see Wang & Wang, 2020).

Results

Preliminary Analyses

The sample sizes across different time points for the younger and older cohorts are displayed in Table 1. Little's missing completely at random (MCAR) test suggested that the missing data was not systematic for the younger cohort (χ^2 = 177.29, p = .17) or the older cohort (χ^2 = 180.05, p = .40). There were some mean-level gender differences, as girls in the younger cohort had higher inhibitory control scores at T2 (ΔM = .46), t (130) = 3.03, p = .003, and T3 (ΔM = .34), t (124) = 2.21, p = .029, and had higher resting RSA scores at T3 (ΔM = .43), t (105)

= 2.00, p = .048, as compared to boys in the younger cohort. For the older cohort, girls scored higher on inhibitory control as compared to boys at T1 (ΔM = .35), t (144) = 2.38, p = .019, and Time 2 (ΔM = .35), t (124) = 2.16, p = .033. Although not consistent across all time points, we considered these gender differences as warranting the inclusion of gender main effects in subsequent analyses. With respect to ethnicity, there was only a significant effect on T2 resting RSA for the younger cohort (with participants coming from multiethnic backgrounds scoring higher in resting RSA [M= 7.06, SD = .90] as compared to participants from Asian backgrounds [M = 5.97, SD = 1.28], F(3,112) = 17.02, p = .012). Since ethnicity was not systematically related to the study variables and we had no theoretical basis to consider its main effect, it was not included in the follow-up analyses in favor of model parsimony.

Zero-order correlations can be found in Table 2. For the younger cohort, parental education (assessed once at T1) was significantly and positively associated with T1 inhibitory control (r = .20, p = .02), and for the older cohort, parental education was significantly and positively associated with T4 inhibitory control (r = .27, p = .009). Parental education was not associated with inhibitory control at other time points or with resting RSA in either age group. Since parental education was not reliably associated with the study variables, we again elected for model parsimony and did not include it in further models. For each age cohort, the associations between inhibitory control and resting RSA with their corresponding measure at the subsequent time point (e.g., between T1 and T2 inhibitory control) were significant, suggesting rank-order stability in each construct across time. Concurrent correlations between inhibitory control and resting RSA (e.g., between T1 inhibitory control and T1 RSA) were examined for the first research aim. The results did not show significant associations between inhibitory control and resting RSA for the younger cohort at any time point. For the older cohort, inhibitory control

and resting RSA had modest yet significant positive correlations at the first three time points, but not at the fourth time point.

Longitudinal Latent Trait Models

In accordance with the results of our preliminary growth curve models[1] (Table 3 and Supplementary Figures 1–4), we ran random and fixed intercepts models to calculate latent trait scores for resting RSA and inhibitory control derived from within-child commonalities across four repeated measures (Geiser, 2020). Then, we tested the correlation between these latent trait scores to determine its strength relative to the concurrent, single-time-point correlations revealed in our previous analytic step. Gender was significantly correlated with some observed variables at different time points in alignment with the previously conducted t-tests, so we retained it in the models as necessary. For the younger cohort, the model examining the association between the latent trait scores of resting RSA and inhibitory control revealed good fit indices ($\chi^2 = 34.85$, $p = .25$, RMSEA = .03, 90% CI = [.00, .07], CFI = .99, TLI = .98, SRMR = .10). The association between the latent factors of resting RSA and inhibitory control was non-significant for the younger cohort ($\beta = -.06$, $p = .568$, see Figure 1). For the older cohort, the same model also showed a good fit to the data ($\chi^2 = 32.17$, $p = .41$, RMSEA = .02, 90% CI = [.00, .06], CFI = .99, TLI = .99, SRMR = .08). The association between the latent traits was significant with a medium or moderate effect size ($\beta = .30$, $p = .002$, see Figure 2). Notably, this effect was almost double in size relative to concurrent correlations between resting RSA and inhibitory control at each time point, which ranged from $r = .07$ to .22 with a pooled effect size of .17 (i.e., small or weak).

[1] Although the analytical focus of the current study was on trait-like stability rather than growth/developmental change, running growth curves is a necessary first step to determine the appropriate latent trait model (see Geiser, 2020).

Discussion

Temperamental inhibitory control is regarded as an important component of positive social-emotional and behavioral development across childhood (Eisenberg et al., 2010; Rhoades et al., 2009; Zhang & Wang, 2020). Therefore, researchers have attempted to identify mechanisms that may explain individual differences in children's inhibitory control. Temperament has long been conceptualized to have a biological basis (Kagan, 1988; Rothbart & Bates, 2006), but studies linking RSA—a widely studied physiological indicator of cardiac regulatory capacity—to inhibitory control have yielded mixed findings. Upon further review, we found that these studies mostly used cross-sectional or short-term longitudinal designs with samples from early childhood, which is when both RSA and inhibitory control are still in relative flux (e.g., El-Sheikh, 2005; Martin et al., 2020). In the present study, we tested associations between latent trait indicators of resting RSA and inhibitory control derived from longitudinal data spanning early *and* middle childhood.

Inhibitory Control, Resting RSA, and Developmental Considerations

We found evidence for rank-order stability in resting RSA and temperamental inhibitory control across three years in total of four annual time points in early and middle childhood. These results indicated that children mostly retained their inhibitory control/RSA advantage (or disadvantage) relative to other children from year to year, speaking in part to the relative consistency *within* each of these constructs. Albeit not the central focus of the current study, we ran preliminary latent growth curves, revealing a slight mean-level increase in inhibitory control for the older cohort across four time points. A significant quadratic trend among the younger cohort also revealed a more rapid mean-level increase across the first three time points with a correction at the fourth time point. We attribute the downturn in inhibitory control at the fourth

time point in the younger cohort to the switch in measurement from the CBQ to TMCQ. Indeed, when the TMCQ measurement at the final time point of the younger cohort is considered as a starting point for the older group, a clearly increasing linear trend is maintained.

These results largely align with previous literature indicating an increase and gradual leveling off of temperamental characteristics across early childhood and into middle childhood (e.g., Bornstein et al., 2019; Martin, 2020). For resting RSA, the significant mean-level increase over time we found for our younger cohort aligns with other developmental studies on the development of RSA across early childhood (e.g., Alkon et al., 2003; Thayer et al., 2009). The slight mean-level decrease we found in our older cohort also fits generally with the mix of extant longitudinal studies suggesting stability (e.g., Hinnant et al., 2011) or a slight decrease (e.g., Salomon, 2005) in resting RSA across middle childhood, perhaps owing to changes in other factors not examined in the current study (e.g., body mass index, onset of puberty; Salomon, 2005; Tabachnick et al., 2019).

With regards to our first research aim of replicating prior cross-sectional research, concurrent associations between resting RSA and inhibitory control *within each time point* were not uniformly significant across cohorts. Specifically, the concurrent associations between resting RSA and inhibitory control were not significant at any time point for the early childhood cohort (i.e., from 4–7 years of age) while the concurrent associations were significant for the first three time points for the middle childhood cohort (i.e., from 8–10 years of age). The concurrent association at age 11 did not reach significance but remained in the expected positive direction. The non-associations in early childhood align with the previous mixed and null results in past literature testing concurrent associations between resting RSA and inhibitory control in the early years (e.g., Kahle et al., 2018; Noten et al., 2019), and may suggest that temperament is in

relatively greater flux during these years. As a result, there may not yet be cohesion amongst various indices of temperament. Our findings from the early childhood cohort also align with previous literature suggesting that the association between biology (e.g., resting RSA) and the broad developmental capacity of inhibitory control may be influenced by other factors, particularly in the early years, which could preclude the detection of a stable bio-temperament relationship. Nonetheless, we maintained the possibility that measuring inhibitory control and RSA repeatedly and extracting commonalities could reduce the influence of noise within any given time point and increase the likelihood of detecting an association.

We thus sought to collect information on resting RSA and inhibitory control across multiple years to extract trait-level factors comprised of commonality across repeated measures. Our rationale was that these latent traits may better reflect the apparent temperamental nature of these constructs and may increase the power to detect an association between them. Mirroring the aforementioned concurrent correlations, the association between latent resting RSA and latent inhibitory control traits was significant for the older cohort, but not for the younger cohort. Moreover, for the older cohort, the standardized correlation between these latent factors was medium in effect size and thus meaningfully larger than the weak correlations identified between resting RSA and inhibitory control measured within each time point. This finding preliminarily suggests that leveraging repeated measures in longitudinal designs to extract trait scores reflecting temperamental consistency may increase power to detect associations between temperamental capacities and their biological correlates. However, it should be noted that the concurrent correlation between inhibitory control and resting RSA in the older cohort was not significant at the fourth time point. This suggests that the latent trait results for that cohort were

primarily driven by the first three time points (i.e., ages 8–10). More longitudinal studies spanning even broader developmental periods are needed to replicate our findings.

Theoretically, higher resting RSA is indicative of better cardiac regulatory capacity, allowing the child to respond more effectively in situations that might necessitate the deferral of a dominant response via inhibitory control (Porges, 2011; Thayer et al., 2009). Therefore, higher resting RSA would be expected to reflect better temperamental inhibitory control. Our results suggest that this association may not become reliably apparent until middle childhood, which echoes previous studies documenting the crystallization of temperament from early to middle childhood (e.g., Bornstein et al., 2019; Putnam et al., 2002). It is plausible that temperamental inhibitory control is less stable and more mutable in the early years of childhood, hence the association between caregiver reports and hypothesized physiological underpinnings may be less stable. With age, temperament —and plausibly the assessment of it—may become more stable and aligned with corresponding physiology. Indeed, RSA also seems to show increases across early childhood (Alkon et al., 2003) and stabilization into late childhood (e.g., Hinnant et al., 2011), an age-graded pattern corroborated in the current study. The gradual stabilization of temperament and physiology may be a contributing factor to the more stable resting RSA–inhibitory control association we found across the middle childhood years. Overall, our results suggest that resting RSA might become a reliable physiological correlate of inhibitory control by middle childhood, particularly when such constructs are measured repeatedly across the developmental period in question and when latent factors are formed that reflect consistency in temperament/biology across years of life, disregarding occasion-specific noise at any single time point or year. Conversely, our overall results suggest that resting RSA may not be a good

indicator of inhibitory control in early childhood (either concurrently via point-in-time assessments or longitudinally via latent traits).

Measurement Considerations

While our main aim in the current study was to test the theoretical biological basis of temperamental inhibitory control, our results may also shed light on the methodological benefits of incorporating biological measurements into the study of temperament. Caregiver assessments of child temperament have been widely used in the literature since most caregivers are highly knowledgeable about their children across different contexts (Yavuz et al., 2022b). Moreover, caregiver reports of temperament have adequate psychometric properties (Rothbart & Bates, 2006). Yet, these assessments may be subject to biases related to parental characteristics and/or their lack of knowledge of normative behaviors in different age groups (Mednick et al., 1996; Kagan et al., 2002). Observational methods are a widely used and effective alternative; however, they may be open to other biases related to measurement and/or coding, as well as to floor and ceiling effect issues when used longitudinally (Adrian et al., 2011; Buchanan, 2016; Herschell et al., 2020; Yavuz et al., 2022b). Furthermore, these methods often need to be adapted over time to account for normative developmental changes, necessitating the use of different scales or observational assessments for different age groups, which makes comparisons across age more difficult. Biological indicators are not subject to informant biases or floor/ceiling effects, and biological equipment can be optimized for standardized delivery within longitudinal frameworks (e.g., by using the same equipment and/or data acquisition settings annually). Therefore, biological correlates of temperament may represent a relatively consistent and impartial supplementary assessment of a child's temperament. The present findings suggest that this may be particularly true for middle childhood samples and within longitudinal analytic frameworks.

Limitations and Future Directions

While the present study focused on resting RSA, other—particularly neurological—biological correlates have been implicated in temperamental inhibitory control (see Fox et al., 2008; Thayer et al., 2009). Examination of multiple biological correlates within a more comprehensive framework would allow for a better understanding of temperament expressed in the brain, body, and behavior. On the other hand, resting RSA offers a relatively accessible, less intrusive, and cheap biological methodology to understand inhibitory control in childhood.

Another limitation of the current study was the use of *resting* RSA as the only indicator of parasympathetic nervous system activation. Though resting RSA is conceptually aligned with temperament as a dispositional, trait-based indicator of self-regulation (Cui et al., 2015; Liew et al., 2011; Porges, 2011), some studies show that *changes* in RSA in different emotion eliciting tasks may also reflect inhibitory control capacities (e.g., Jimenez-Camargo et al., 2017; Utendale et al., 2014; Sulik et al., 2015). Therefore, future studies might benefit from examining task-based changes in RSA alongside resting levels to gain a more sensitive understanding of the relationship between RSA and inhibitory control.

Although the general retention rate across years and age cohorts in the current study was acceptable (between 84% to 95.5%) according to similar existing longitudinal studies (Moilanen et al., 2009; Qiu et al., 2023), the retention rate between the first and final time points for the older age cohort was comparatively lower (64%). Missing data analyses did not suggest systematic issues, but the sample size was still reduced for concurrent correlational results within each time point, specifically for the unexpected non-significant correlation between resting RSA and inhibitory control in the last time point for the older age cohort. Acknowledging that collecting and processing physiological data presents significant time and resource challenges,

future psychophysiological longitudinal studies with larger samples are needed to assess whether and to which extent attrition affected the current study results.

Finally, we relied on caregiver reports of child temperamental inhibitory control, which, as discussed above, may be prone to biases (Adrian et al., 2011). Even though parents possess intimate knowledge of their children, their perspectives should ideally be supported by supplemental agreement from other informants (e.g., the other caregiver, the child's teachers) or observational assessments targeting specific behaviors reflective of inhibitory control. Moreover, we used two parent-reported temperament measures (i.e., CBQ and TMCQ) at different points throughout the current study to ensure developmental appropriateness, which might be associated with the results. Despite these questionnaires having overlapping items and being designed to assess the same construct, the change from one to the other for the younger age cohort at the final time point might have impacted their growth model.

Conclusions

In general, our results suggest that trait resting RSA is a physiological indicator of temperamental inhibitory control in middle childhood. However, this physiology-temperament link might not yet be stable in earlier years. It may take time for individual differences in inhibitory control to become reliably based in characteristics of the parasympathetic nervous system. Other biological indicators, including those in the central nervous system, may be more sensitive indicators of temperamental differences in infancy and early childhood. Extracting "temperament" from repeated measures in long-term longitudinal frameworks may increase the likelihood of identifying and thus understanding the biological bases of inhibitory control and other temperamental capacities.

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Table 1

Descriptive Statistics Across Time Points by Cohort

	Younger Cohort (ages 4–7)				Older Cohort (ages 8–11)			
		Age	IC	RSA		Age	IC	RSA
	n	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*n*	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
T1	150	4.53 (.30)	3.99 (.92)	6.45 (1.19)	150	8.53 (.29)	3.74 (.89)	7.03 (1.13)
T2	132	5.57 (.35)	4.19 (.90)	6.54 (1.25)	126	9.59 (.33)	3.84 (.91)	6.98 (1.03)
T3	126	6.55 (.33)	4.42 (.87)	6.81 (1.13)	106	10.61 (.33)	4.02 (.93)	6.80 (1.15)
T4	119	7.56 (.32)	3.41 (.97)	6.96 (.84)	96	11.58 (.33)	3.99 (.94)	6.68 (1.07)

Table 2

Zero-Order Correlations Between Main Study Variables for the Younger (Below Diagonal) and Older (Above Diagonal) Cohorts

	1	2	3	4	5	6	7	8
1. T1 IC	—	.18*	.66***	.20*	.71***	.22*	.57***	.18
2. T1 RSA	-.03	—	.08	.56***	.08	.45***	.27**	.41**
3. T2 IC	.68***	-.03	—	.22*	.69***	.24**	.63***	.20*
4. T2 RSA	.04	.49***	-.03	—	.14	.56***	.09	.55***
5. T3 IC	.61***	.02	.64***	.03	—	.21*	.65***	.11
6. T3 RSA	.08	.36***	.00	.55***	.05	—	.16	.57***
7. T4 IC	.49***	-.05	.56***	.01	.63***	.01	—	.07
8. T4 RSA	-.05	.40***	-.07	.64***	-.21*	.49***	-.17†	—

Note. IC = inhibitory control. RSA = respiratory sinus arrhythmia . ***$p < .001$; **$p < .01$; *$p < .05$

Table 3

Growth Curve Models for the Younger and Older Cohorts

		Younger Cohort (ages 4-7)			Older Cohort (ages 8-11)		
		b	*SE*	*p*	*b*	*SE*	*p*
Inhibitory Control	Mean – *I*	4.14	.08	< .001	3.74	.07	< .001
	Mean – *S*	-.04	.04	.286	.09	.03	< .001
	Mean – *Q*	-.30	.03	< .001	-.02	.03	.429
	Variance – *I*	.53	.10	< .001	.563	.10	< .001
	Variance – *S*	-.03	.02	.154	.01	.02	.567
	Variance – *Q*	-.02	.02	.479	-.02	.02	.267
Resting RSA	Mean – *I*	6.39	.10	< .001	7.03	.09	< .001
	Mean – *S*	.20	.03	< .001	-.10	.04	.009
	Mean – *Q*	.02	.04	.619	.01	.04	.848
	Variance – *I*	.78	.18	< .001	.73	.16	< .001
	Variance – *S*	.03	.03	.406	.05	.03	.130
	Variance – *Q*	.01	.05	.900	.00	.04	.930

Note. RSA = respiratory sinus arrhythmia. *I* = intercept, *S* = linear, *Q* = quadratic.

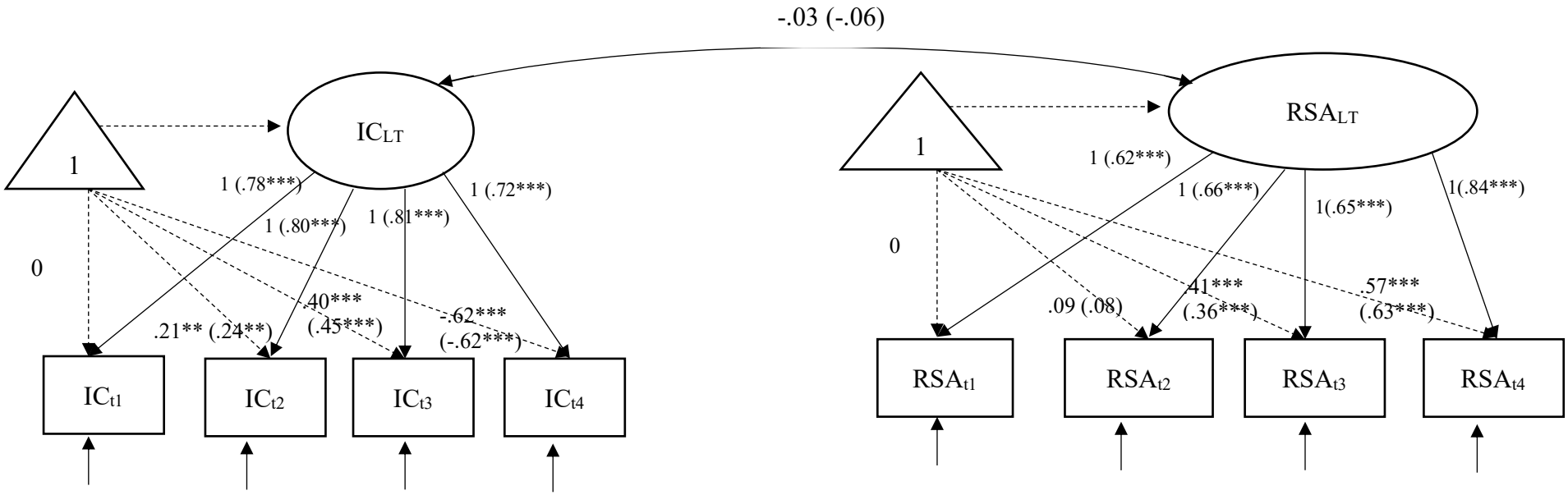

Figure 1. Path diagram showing the correlation between trait inhibitory control and trait resting RSA (random and fixed intercepts model) for the younger cohort.

Note. IC = inhibitory control. RSA = respiratory sinus arrhythmia. Unstandardized and (standardized) results reported. IC_{LT} = Latent trait of inhibitory control across 4 time points. RSA_{LT} = Latent trait of resting RSA across 4 time points. ** $p < .01$. *** $p < .001$.

.

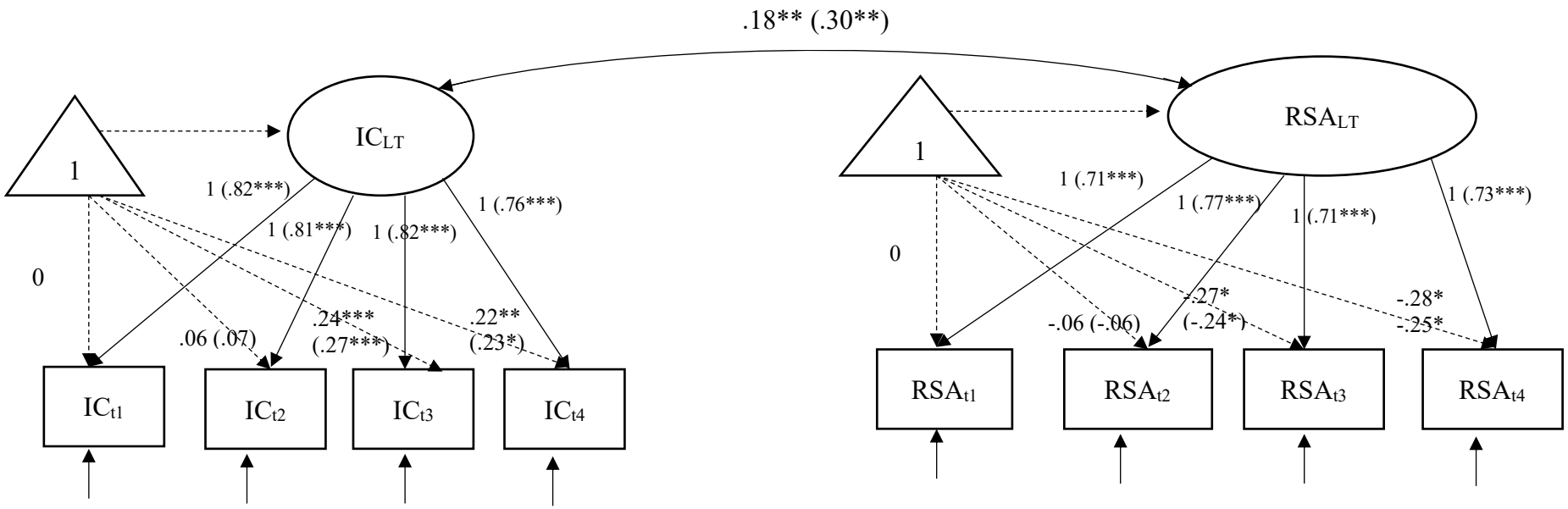

Figure 2. Path diagram showing the correlation between the trait inhibitory control and trait resting RSA (random and fixed intercepts model) for the older cohort.

Note. IC = inhibitory control. RSA = respiratory sinus arrhythmia. Unstandardized and (standardized) results reported. IC_{LT} = Latent trait of inhibitory control across 4 time points. RSA_{LT} = Latent trait of resting RSA across 4 time points. * $p < .05$. ** $p < .01$. *** $p < .001$.