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Authors
Palser, Eleanor R
Morris, Nathaniel A
Roy, Ashlin RK
et al.

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Children with developmental dyslexia show elevated parasympathetic nervous system activity at rest and greater cardiac deceleration during an empathy task

Authors: Eleanor. R. Palser[1], Nathaniel A. Morris[1], Ashlin R. K. Roy[1], Sarah R. Holley[2,3], Christina R. Veziris[1], Christa Watson[1], Jessica Deleon[1], Zachary A. Miller[1], Bruce L. Miller[1], Maria Luisa Gorno-Tempini[1,3], & Virginia E. Sturm[1,3*]

Affiliations: 1- Department of Neurology, University of California, San Francisco, CA 94158, USA.

2- Psychology Department, San Francisco State University, San Francisco, CA 94132, USA.

3- Department of Psychiatry, University of California, San Francisco, CA 94131, USA.

*Corresponding author: Dr. Virginia Sturm, virginia.sturm@ucsf.edu, 415 476-8618, Weill Institute for Neurosciences, 675 Nelson Rising Lane, Suite 190, San Francisco, California 94143, USA

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Abstract

Reading difficulties are the hallmark feature of dyslexia, but less is known about other areas of functioning. Previously, we found children with dyslexia exhibited heightened emotional reactivity, which correlated with better social skills. Whether emotional differences in dyslexia extend to the parasympathetic nervous system—an autonomic branch critical for attention, social engagement, and empathy—is unknown. Here, we measured autonomic nervous system activity in 24 children with dyslexia and 24 children without dyslexia, aged 7 – 12, at rest and during a film-based empathy task. At rest, children with dyslexia had higher respiratory sinus arrhythmia (RSA) than those without dyslexia. Cardiac deceleration during the empathy task was greater in dyslexia and correlated with higher resting RSA across the sample. Children with dyslexia produced more facial expressions of concentration during film-viewing, suggesting greater engagement. These results suggest elevated resting parasympathetic activity and accentuated autonomic and behavioral responding to others' emotions in dyslexia.

Key Words
Social behavior; compassion; emotion recognition; neurodiversity

1. Introduction

Developmental dyslexia (henceforth, dyslexia) is a neurodevelopmental disorder characterized by pervasive difficulties in learning to read despite adequate education and general intelligence. Rates of dyslexia vary between 5 and 17% due to variability in diagnostic criteria and demographic factors, with reading difficulties frequently persisting into adulthood (Shaywitz, 1998; Silani et al., 2005). Although dyslexia is thought to arise from a reduced ability to segment words into smaller phonological sound units and to associate these sound units with written words (Bruck, 1992; Caravolas et al., 2005; Paulesu et al., 2001; Silani et al., 2005; Ziegler et al., 2003), the condition is heterogeneous and not all individuals show phonological processing impairment (Shaywitz, 1998; Bradley & Bryant, 1983; Frith, 1999; Lyon et al., 2003; O'Brien et al., 2012).

In addition to reading difficulties, affective symptoms (e.g., anxiety or depressed mood) are common in dyslexia and extend beyond academic situations (Carroll & Iles, 2006; Carroll et al., 2005). Affective symptoms may reflect dysregulation of underlying systems that produce emotions (Etkin, 2009; Teasdale, 1988), but little is known about emotion system functioning in dyslexia. In our view, emotions are brief functional states accompanied by cascades of autonomic nervous system and motor activity that disrupt homeostasis and influence behavior and experience (Levenson, 2003).

In a recent study (Sturm et al., 2021), we used a laboratory-based approach to investigate emotional reactivity in children with dyslexia. We found children with dyslexia had greater autonomic nervous system reactivity—larger increases in skin conductance level (SCL) and respiration rate—and greater facial behavior while watching emotionally evocative film clips than children with no reading difficulties. Among the children with dyslexia, those with greater facial expressivity during film-viewing had worse symptoms of anxiety and depression as well as better social skills, per parent reports. These findings suggested that elevated emotional reactivity in dyslexia may be associated with greater vulnerability to affective symptoms, but also more competency in interpersonal settings. Such social skills may represent a strength or area of resilience in children with dyslexia that, when nurtured, may help protect them from the potential negative effects of their learning differences (Haft et al., 2016).

Although greater emotional reactivity may relate to better social skills in dyslexia, our previous study did not investigate the role of the parasympathetic nervous system. Within the autonomic nervous system, the sympathetic and parasympathetic branches are critical for both homeostatic maintenance and emotion generation (Saper, 2002). While activation of the sympathetic nervous system tends to increase metabolic output and support mobilization behaviors, engagement of the parasympathetic nervous system often slows metabolic activity and supports growth and restoration (Craig, 2005; Levenson, 2003; Porges, 2001; Taylor et al., 2000). Together, both branches of the autonomic nervous system contribute to emotions, empathy, and social behavior by increasing or decreasing activity in targeted organs and muscles throughout the body in response to prevailing conditions and goals. Activity in the parasympathetic nervous system fluctuates with moment-to-moment engagement and disengagement with the environment and, thus, is important for interpersonal sensitivity, attention allocation, and social attunement (Porges, 2007; Thayer & Lane, 2000; Friedman, 2007; Guiliano et al., 2018; Richards, 1987).

During laboratory tasks, parasympathetic activity is often measured by quantifying cardiac deceleration, a physiological change largely attributed to greater vagal inhibition of the heart (Berntson et al., 1993; Danielsen et al., 1989; Holstege, 1989; Onai et al., 1987; Richards & Casey, 1991), and respiratory sinus arrhythmia (RSA), a measure of heart rate variability thought to reflect oscillating vagal influences on the heart across the breathing cycle (Berntson et al., 1997; Grossman & Svebak, 1987). Cardiac deceleration occurs when people orient to novel information and varies with ongoing attentional demands (Lacey & Lacey, 1977) as well as task novelty, ambiguity, or uncertainty (Corcoran et al., 2021). By reducing metabolic activity, cardiac deceleration in response to salient stimuli has been hypothesized to promote sensorimotor processing (Porges, 2001, 2007).

Heart rate variability measures taken at rest, including RSA, have also been associated with performance in multiple cognitive and affective domains, with higher heart rate variability relating to flexible, adaptive responding as well as a host of social and emotional advantages from the earliest days of life (Beauchaine, 2001). In infants and children, higher resting heart rate variability is associated with greater active engagement with the environment (Richards & Cameron, 1989), enhanced sustained attention (Suess, Porges et al., 1994), and higher emotional reactivity (Stifter et al., 1989). Whereas children and adolescents with behavioral and social disturbances often have lower resting heart rate variability (Condy et al., 2017; Eisenberg et al., 2012; Pine et al., 1996), those with higher resting heart rate variability show greater facial expressions of concern in response to others in distress (Fabes et al., 1993) as well as greater dispositional helpfulness (Fabes et al., 1993), sympathy (Taylor et al., 2015), and prosocial tendencies (Fabes et al., 1994; Miller et al., 2015). In adults too, higher resting heart rate variability is also associated with socioemotional benefits. Adults with higher resting heart rate variability report greater empathy (Lischke et al., 2018), optimism and agreeableness (Oveis et al., 2009), and feelings of social acceptance (Geisler et al., 2013). They also display more positive emotions (Isgett et al., 2017) and cooperative behaviors (Beffara et al., 2016) during social interactions. Lower resting heart rate variability, in contrast, is a feature of numerous clinical disorders that manifest across the lifespan including depression (Carney et al., 2000; Koenig et al., 2016; Rechlin et al., 1994), anxiety (Friedman & Thayer, 1998; Thayer et al., 1996; Viana et al., 2019; Watkins et al., 1998), and frontotemporal dementia (Sturm et al., 2018).

In the present study, we investigated resting parasympathetic nervous system activity in children with dyslexia—a reading disorder in which we have found a linkage between emotional reactivity and social skills—and its relationship to autonomic and behavioral responding to others' emotions. To assess empathy, children watched film clips depicting characters displaying target emotions, and we measured their reactions to and recognition of those characters' emotions. While the ability to name the emotions of others (i.e., emotion recognition) is considered a form of cognitive empathy that requires verbal labeling, our primary interest was in emotional empathy, a form of empathy not dependent on language (Pasalich et al., 2014; Rueda et al., 2014). Emotional empathy allows individuals to share others' emotions via autonomic and behavioral mirroring systems (Hatfield et al., 1993). Importantly, the nature of these reactions may vary across people and reflect different types of empathic responses (Decety, 2011; Decety & Meyer, 2008). While some forms of emotional empathy can increase self-focused attention (Batson et al., 1987; Eisenberg et al., 1994), feelings of distress (Decety, 2010; Decety & Cowell, 2014), and sympathetic nervous system activity (El-Sheikh et al., 1989; Liew et al., 2010), other forms of emotional empathy foster other-oriented attention, feelings of compassion, and parasympathetic nervous system activity (Eisenberg et al., 1994; Decety & Lamm, 2011; Hastings & Miller, 2014; Miller et al., 2015; Levenson & Ruef, 1992; Oveis et al., 2010; Stellar et al., 2015). As the parasympathetic nervous system activity is associated with attention,-empathy, and social sensitivity, we expected that, if resting RSA is elevated in dyslexia, it would relate to differences in autonomic and behavioral responses to others' emotions in the film clips. Given the possible contribution of language to cognitive empathy performance, however, we did not expect children with dyslexia would have better emotion recognition skills (Im-Bolter et al., 2013; Miller, 2009).

2. Methods

2.1. Participants

Forty-eight participants, 24 children with dyslexia and 24 children without dyslexia, were included in the present study. All participants were fluent English speakers between the ages of 7 and 12 years of age. Both groups were comprised of 14 male and 10 female participants. The study protocol was approved by the institutional Human Research Protection Program. Participants provided verbal assent, and their guardians provided written informed consent.

Participants were recruited through the University of California, San Francisco (UCSF) Dyslexia Center, and those with a history of diagnosed or suspected learning differences underwent a comprehensive multi-disciplinary evaluation including a clinical interview and neurological examination with a neurologist as well as academic, neuropsychological and language testing with trained evaluators. For inclusion in the dyslexia cohort, children were required to have a prior diagnosis of dyslexia and a diagnosis of dyslexia at the time of the study. The majority (90%) were attending specialist schools for children with learning differences. Children with no dyslexia (or other notable history of academic difficulties) were recruited to the UCSF Dyslexia Center through local schools and participated in an abbreviated evaluation that included a clinical interview and neurological examination as well as abridged academic, neuropsychological, and language testing.

Children were excluded if they had a history of acquired brain injury, known genetic condition that impacts cognition and development, psychiatric disorder, or neurodevelopmental condition (other than dyslexia). In general, medication usage across the sample was minimal. Fifteen percent of the participants were taking allergy medications at the time of the study (a rate that was comparable across the children in both groups). One participant reported taking a stimulant medication within the last two days, and none reported taking anxiolytics, antidepressant medications, or beta-blockers. See Table 1 for demographic and cognitive information.

Table 1

Demographic, nonverbal reasoning, and reading characteristics of the sample. *Range, mean (M), and standard deviation (SD) are provided. Children with and without dyslexia did not differ on age, sex, BMI, or nonverbal reasoning ability. Language and reading (variables d – g) were only assessed in children with dyslexia.*

Measure	**With Dyslexia**			**Without Dyslexia**		
	Range	***M***	***SD***	**Range**	***M***	***SD***

N		24			24	
Sex (male: female)		14:10			14:10	
Age[a]	7–12	9.8	1.5	7–12	10.2	1.6
BMI[b]	13.3–21.5	17.1	2.8	12.2–23.3	17.4	2.6
Nonverbal reasoning ability [c]	31–93	69.0	21.3	16–99.6	75.9	20.3
Language comprehension [d]	73-98	96.8	6.6	*NA*	*NA*	*NA*
Letter-word identification [e]	9–86	30.7	23.8	*NA*	*NA*	*NA*
Word attack [e]	0.3–75	25.9	22.2	*NA*	*NA*	*NA*
Sight word efficiency [f]	0.1–75	17.2	22.3	*NA*	*NA*	*NA*
Phonemic decoding efficiency [f]	0.7–53	15.1	15.1	*NA*	*NA*	*NA*
Reading rate [g]	0.4–63	20.4	16.3	*NA*	*NA*	*NA*
Reading accuracy [g]	1–25	10.4	8.3	*NA*	*NA*	*NA*
Reading fluency [g]	0.4–25	13.5	9.6	*NA*	*NA*	*NA*
Reading comprehension [g]	4–63	26.8	16.5	*NA*	*NA*	*NA*

Notes: a) Age reflects chronological age, given in years. b) BMI denotes body mass index. c) Nonverbal reasoning ability reflects percentile score on the Wechsler Abbreviated Scale of

Intelligence (WASI; Wechsler, 1999). d) Language comprehension reflects percentage correct on the Curtiss-Yamada Comprehensive Language Evaluation-Receptive Test (CYCLE-R; Curtiss, 1988). e) Letter-word identification and word attack reflect percentile scores on the Woodcock-Johnson IV (Schrank et al., 2014) subscales. f) Sight word efficiency and phonemic decoding efficiency reflect percentile scores on the Test of One-Word Reading Efficiency-Version 2 (TOWRE-2; Torgesen et al., 2012) subscales. g) Reading rate, accuracy, fluency, and comprehension scores reflect percentile scores on the Gray Oral Reading Ability-Fifth Edition (GORT-5; Wiederholt & Bryan, 2012).

2.2. Neuropsychological Assessment

All participants completed Matrix Reasoning, a test of nonverbal reasoning from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), with a neuropsychologist and were included in the present study if their performance was at least above the 9th percentile (i.e., above the impaired range). Children with dyslexia also completed a modified Eriksen flanker task, included in the National Institutes of Health Toolbox Cognitive Function Battery, as a measure of sustained attention (Eriksen & Eriksen, 1974; Kramer et al., 2014). This well-validated task induces response conflict by requiring participants to make a button-press indicating the direction in which a target arrow points. The target arrow is surrounded by arrows that either point in the same (congruent) or opposite (incongruent) direction. Percentile scores were derived using published norms and reflect the combination of accuracy and reaction time on incongruent trials (Kramer et al., 2014).

Attention problems in everyday life were assessed in the children with dyslexia using the Attention Problems subscale from the Behavior Assessment System for Children, Second Edition

(BASC-2) child (ages 6 – 11) and adolescent (ages 12 – 21) parent rating scale forms (Reynolds & Kamphaus, 2004). The parent is asked to rate each item according to the frequency of the behavior on a four-point scale, ranging from N (*never*), S (*sometimes*), O (*often*), to A (*almost always*). The BASC-2 scoring algorithm standardizes participants' scores within their age group, making scores on the child and adolescent forms equivalent. Item raw scores were summed, and subscale scores were converted into standardized *T* scores (mean = 50; standard deviation = 10) for analysis. The parents of five children declined to complete this measure; therefore, data were available for a total of 19 children with dyslexia.

2.3. Academic Assessment

Single-word reading was assessed with Letter-Word Identification and Word Attack, untimed measures from the Woodcock-Johnson IV (Schrank et al., 2014), and the Test of One-Word Reading Efficiency-Version 2, a timed measure (TOWRE-2; Torgesen et al., 2012). Paragraph reading was assessed using the Gray Oral Reading Ability - Fifth Edition test (GORT-5; Wiederholt & Bryan, 2012). Testing confirmed that all children with dyslexia had at least one low reading score (≤ 25th percentile). This more liberal cut-off for reading scores was used because most of the children had received extensive remediation at their schools. Nevertheless, most of the children with dyslexia (75%) fell below the 10th percentile on at least one reading measure. Language comprehension was assessed using the Curtiss-Yamada Comprehensive Language Evaluation-Receptive Test (CYCLE-R; Curtiss, 1988). The CYCLE-R consists of a series of subtests tapping specific semantic, syntactic, and morphological structures. Each test requires the participant to either point to an item in the test picture book, or manipulate an object, in response to a complex sentence read aloud by the examiner. This test is particularly sensitive to participants' ability to deploy attention processes in order to parse verbal language (Dronkers et al., 2004).

Two of the children in the dyslexia sample were missing Matrix Reasoning scores, and two were missing reading scores; in these instances, their original diagnoses of dyslexia were trusted.

2.4. Laboratory Assessment of Emotion

2.4.1. Physiological Instruments

Continuous recordings of autonomic nervous system activity were obtained during the resting baseline and empathy film tasks using Biopac Systems Inc. (biopac.com; California, USA) MP150 bioamplifiers and a computer equipped with data acquisition software. To record cardiac activity, three disposable electrodes were placed in a bipolar configuration on opposite sides of the participant's chest, and an electrocardiogram was recorded at a sampling rate of 1000 Hz. Respiration was measured with a pneumatic bellows-based respiration transducer stretched around the abdominal region (Biopac TSD221-MRI belt). To record electrodermal activity, a Biopac GSR100c amplifier was used to pass a small voltage between two Ag/Acl Silver 8mm EL258s shielded electrodes (using an electrolyte of sodium chloride) attached to the palmar surface of the middle phalanges of the ring and index fingers of the non-dominant hand.

2.4.2. Procedure

Participants were seated in a comfortable chair in a well-lit testing room. All stimuli were presented on a 21.5-inch computer monitor placed 4.25 feet in front of them. All audiovisual instructions were presented using ePRIME (version 3.0, Psychology Software Tools, Pittsburgh, PA). During the tasks, the experimenter left the testing room, observing the participant from a nearby control room with a semi-concealed camera and communicating via an intercom system. Participants were informed they would be video recorded prior to the start of the testing session. They completed a battery of tasks designed to assess resting baseline physiology, emotional reactivity, empathy, and emotion regulation. Only the resting baseline and empathy tasks were included in the present study. All participants completed the tasks in the same order. Emotion word knowledge was completed first, followed by the resting baseline. The empathy films task followed, after other interim tasks. Following completion of the laboratory tasks, the physiological sensors were removed, and participants were debriefed by the experimenter.

2.4.3. Tasks

2.4.3.1. Emotion Word Knowledge

At the beginning of the laboratory session, participants completed a task that assessed whether they understood the meaning of each of the emotion terms that would be used throughout the assessment. Participants were asked, “For each question, you will see an emotion word at the top of the screen. Pick the situation where you would feel the emotion.” They were presented with three choices for each emotion term. The experimenter reviewed any questions that were answered incorrectly and explained the correct responses to the participant. This step was taken to ensure that participants understood all of the emotion terms that would be used throughout the testing session. If participants asked for clarification about the meaning of any word later in the session, the experimenter reminded them of the meaning as often as needed.

2.4.3.2. Resting Baseline

To obtain measures of resting autonomic nervous system activity, participants were asked to sit quietly and watch a black “X” on a white computer screen for a two-minute period. Participants were provided with the following instructions: “For the next task, you will sit quietly for two minutes. Please relax and try to clear your mind when you see an ‘X’ on the screen. Watch the ‘X’, please.”

2.4.3.3. Empathy Films Task

Participants watched a series of film clips, and each clip showed a person displaying a specific emotion, an approach that has been used successfully in prior studies of empathy (e.g., Goodkind et al., 2015). At the beginning of the task, participants were presented with the following instructions, “In the next task you will watch movies. After each movie, we will ask you some questions. We will ask you how a person in the movie feels. If you find the video too upsetting, please close your eyes. Before each movie, you will see an ‘X’ on the screen. Please relax and try to clear your mind when you see the ‘X’ on the screen. Let’s begin.”

Each trial began with a 30-second pre-trial baseline period in which participants watched a black “X” on a white computer screen. They then viewed a 30-second film clip that included a target character displaying one of nine emotions (i.e., amusement, affection, embarrassment, sadness, fear, disgust, anger, enthusiasm, or pride). The amusement clip showed a young girl smiling and laughing with a woman in a store (*Safe Haven*, 2013); the affection clip showed a scene of a man walking up to a woman and embracing tenderly (*When a Man Loves a Woman*, 1994); the embarrassment clip showed a woman tripping while walking down the stairs and being caught by a man (*She’s All That*, 1999); the sadness clip showed a woman crying while reading a letter in a car (*The Notebook*, 2004); the fear clip showed a woman being confronted by a man in her house, screaming, and running away (*Ferris Bueller's Day Off*, 1986); the disgust clip showed a woman vomiting as an alien is dissected (*Starship Troopers*, 1997); the anger clip showed two men shouting at each other through a car door (*Scary Movie 4*, 2006); the enthusiasm clip showed a man dressed in an elf costume shouting and jumping in excitement (*Elf*, 2003); the pride clip showed a man smiling while watching a child who had won a trophy (*Searching for Bobby Fischer*, 1993). Pilot testing in an independent sample of healthy children indicated that these film clips conveyed the target emotions. Each participant viewed the film clips in the same order, as listed above.

After viewing each film clip, participants were asked a series of questions. First, they were asked about the content of each film clip to ensure that they had paid attention during the task. They were provided three choices and were asked to identify the correct response. Second, participants were asked if they had seen the film from which the clip was taken, which provided a measure of their prior familiarity with the stimuli. Third, participants were asked to label the target character's primary emotion. They were provided with a visual reminder of the character from the film (during a neutral moment, so as not to influence their response) and asked, "What emotion did this person feel most strongly?" They selected from the following choices: "afraid," "love or affection," "angry," "amazement or awe," "disgusted," "embarrassed," "excited or enthusiastic," "happy or amused," "proud," "sad," "surprised," or "no emotion." For some choices, we provided two words for one emotional state because the more precise emotion label is less well-known to younger children; in these cases, either of the two choices was considered correct. Participants provided verbal responses, which were recorded by the experimenter.

2.4.4. Measures

2.4.4.1. Physiological recordings

Physiological data were processed offline using a custom pipeline scripted in AcqKnowledge software (v5, biopac.com). The physiological measures we focused on were inter-beat interval (a measure of heart rate), total respiratory cycle time (T_{TOT}, a measure of respiration rate), respiratory sinus arrythmia (RSA), and skin conductance level (SCL). Briefly, algorithms identified and marked the signature components of each waveform, and these markers were then visually inspected for errors and noise. Inter-beat interval was calculated as the time between successive R-waves. T_{TOT} was quantified as the time, in milliseconds, between successive inspirations. RSA was calculated based on changes in inter-beat interval associated with respiration using the peak-to-valley method (Grossman, 1983). This is a time-domain based index of vagally mediated heart rate variability, which measures the difference between the shortest inter-beat interval during inspiration and the longest inter-beat interval during expiration.

2.4.4.2. Emotional facial behavior

Video recordings of the empathy films task were coded by trained coders who were blind to the study goals and hypotheses with Noldus version 13.0 software (Noldus Technologies, Leesburg, VA). Participants' emotional facial expressions while watching each 30-second film were coded on a second-by-second basis using a modified version of the Emotional Expressive Behavior coding system (Gross & Levenson, 1995). The original system was developed to capture a broad range of expressive behaviors, with a particular focus on those related to emotions. The modified scale, used here, combines the categorical aspects of the Emotional Expressive Behavior coding scale and the Facial Affect Coding System (Ekman & Friesen, 1976). Specifically, categories of emotions were coded, and the criteria used for each category were defined in terms of the specific facial muscles that accompany each emotion expression. Thus, the resultant system used more objectively defined coding criteria, which enabled greater coding precision. Coders rated the presence of the following categories of emotional facial behaviors: interest, concentration, anger, sadness, disgust, fear, contempt, happiness/amusement, surprise, embarrassment, shame, and pride. All behaviors were rated on a three-point intensity scale: 1 (*slight but noticeable*), 2 (*moderate*), or 3 (*strong*). When none of these expressive behaviors were present, the face was coded as neutral. Codes were mutually exclusive, and, thus, blends of emotion were not permitted in this system.

Fifteen percent of the videos were rated by multiple coders; interrater reliability was excellent (Cohen's kappa = .82; Cohen, 1960; Fleiss, 1981). We summed the intensity scores across the 30 seconds of each trial for each of the following emotion codes: anger, concentration, contempt, disgust, embarrassment, fear, happiness/amusement, interest, sadness, and surprise. These summed intensity scores were then averaged to provide a total emotional facial behavior score for each trial. Emotional facial behavior was calculated in this way to reduce multiple comparisons and to capture the wide range of reactions that can occur in response to others' emotions (Mauersberger et al., 2015). Codes for each category of emotional facial behavior were also examined in exploratory follow-up analyses.

2.4.4.3. Self-Report Measures

2.4.4.3.1. Emotion word knowledge. Participants' total emotion word knowledge score was calculated by summing their total correct responses. Higher scores indicated greater knowledge of emotion terms (maximum score = 15).

2.4.4.3.2. Film Content. Reponses to the question regarding the content of each film, a measure of attention during the task, were scored (1 = correct, 0 = incorrect), and a total score was computed for each participant (maximum score = 9).

2.4.4.3.3. Film Familiarity. Reponses to the question regarding participant's prior familiarity with each film were scored (1 = seen it before, 0.5 = not sure, 0 = not see before), and a total score was computed as the percentage endorsed as previously seen for each participant.

2.4.4.3.4. Emotion Recognition. Responses to the question regarding the target character's primary emotion were scored (1 = correct, 0 = incorrect), and a total emotion recognition score was computed as the percentage of correct trials in which participants correctly identified the emotion.

2.4.4.5. Body mass index

Body mass index (BMI) was calculated for each participant from the height and weight measurements using the Child and Teen BMI Calculator from the Centers for Disease Control and Prevention. One participant with dyslexia and one participant without dyslexia had missing data, resulting in BMI data for 46 participants.

2.5. Data Analysis

Analyses were carried out in R Project (R Core Team, 2017). Outliers in the raw physiological data were considered to be +/- three standard deviations from the mean level during the trial; these periods were interpolated if their duration was three seconds or less and deleted if their duration was greater than three seconds. For each physiological channel, second by second averages were then exported for analysis. Any trials that contained greater than 25%

deletions were discarded. Finally, trials considered to be +/- three standard deviations from the group mean were deleted (less than 25% of trials, see Supplementary Tables 1-4). Heart rate rhythms (e.g., heart rate variability) rarely meet the requirements of parametric analyses (due to intrinsic non-stationarity and non-sinusoidal characteristics) (Berntson et al., 1993); therefore, we performed the recommended log-transform of RSA scores to normalize the distribution (Porges & Bohrer, 1990; Riniolo & Porges, 1997).

For the resting baseline task, we computed a mean level of each physiological channel across the two minutes. For the empathy films task, we computed reactivity scores for each physiological channel by subtracting the mean level during the 30-second pre-trial baseline from the mean level during each 30-second trial.

Two-tailed tests were used in all statistical analyses. *T*-tests and chi-square tests were used to assess group differences in BMI and sex, respectively. As age and nonverbal reasoning data were non-normally distributed, they were analyzed using non-parametric Mann-Whitney tests. Multiple linear regressions were used to test for group differences in resting baseline physiology. Cohen's f^2 is reported as measure of effect size. According to Cohen's (1988) guidelines, $f^2 \geq .02$, $f^2 \geq .15$, and $f^2 \geq .35$ represent small, medium, and large effect sizes, respectively.

Mixed effects models were used to test for group differences in physiological reactivity and total emotional facial behavior during the empathy films task. Random intercepts were specified for each participant and each trial (entered as a categorical variable and dummy-coded with nine levels), and fixed effects were specified for group, age, and sex. Group and sex were both entered as categorical variables and dummy-coded with two levels. To obtain *p*-values as an indication of statistical significance, mixed effects models were compared using likelihood ratio tests via analysis of variance (ANOVA) (Bolker et al., 2009). Model residuals were assessed for normality using diagnostic Q-Q plots. In the interest of brevity, we only report on the fixed effects of interest (group and group by trial interactions) in the Results section but see Supplementary Materials for unstandardized coefficients for all effects.

The field has yet to reach consensus on whether respiration rate and, to a lesser extent, heart rate should be accounted for in analyses of RSA (see Allen, Chambers, & Towers, 2007; Berntson et al., 1997; Denver, Reed, & Porges, 2007; Grossman & Taylor, 2007 for discussion). Briefly, there is debate as to whether RSA also reflects variability in respiration and cardiac activity that is not under central vagal control. This is particularly relevant in instances where respiration and/or heart rates differ between groups or conditions (Grossman, Karemaker, & Wieling, 1991; Houtveen, Rietveld, & de Geus, 2002). As such, we report RSA analyses with and without including T_{TOT} and inter-beat interval as additional covariates.

As the emotional facial behavior codes reflect brief instances of behavior, when considered individually we averaged each code across trials. Multiple linear regressions were then used to test for group differences in each emotional facial behavior code at the mean level. We report these exploratory analyses without correction for multiple comparisons because of our relatively small sample size. Multiple linear regressions were also used to test for a relationship between resting RSA and autonomic reactivity variables that may index parasympathetic change during the empathy task (i.e., inter-beat interval, T_{TOT}, RSA), averaged across trials.

Multiple linear regressions were run to examine whether the groups differed on the control tasks. Post hoc bivariate correlation analyses were conducted to examine potential associations between the laboratory-based measures and other cognitive and behavioral measures (i.e., language comprehension, reading comprehension, flanker performance, and parent-reported attention problems); see Supplementary Materials for results. Pearson's correlations were used when these variables were normally distributed; otherwise, Spearman's correlations were used.

3. Results

Participants with and without dyslexia did not show group level differences in sex, $X^2(1) = 0.00$, $p = 1.000$, age, $W = 327.50$, $p = .411$, BMI, $t(43.93) = 0.36$, $p = .724$, or nonverbal reasoning, $W = 311.00$, $p = .305$. Given their potential influence on emotional responding, however, age and sex were included as covariates in all analyses (Allen & Matthews, 1997; Boyce, Alkon, Tschann, Chesney, & Alpert, 1995; Casey 1993; Eisenberg et al., 1988; Katz, Kellerman, & Siegel, 1980; Malatesta-Magai, Leak, Tesman, & Shepard, 1994). See also the Supplementary Materials for results reported separately by sex.

Resting Baseline Physiology

The multiple linear regressions revealed that the children with dyslexia had higher resting RSA, $B = 0.39$, $t = 2.81$, $p = .007$, $f^2 = .78$, and greater resting inter-beat interval, $B = 57.83$, $t = 2.28$, $p = .028$, $f^2 = .64$, than those without dyslexia (see Figure 1). The groups did not differ in resting T_{TOT}, $B = -177.58$, $t = -0.58$, $p = .563$, $f^2 = .18$, or resting SCL, $B = 0.82$, $t = 1.22$, $p = .229$, $f^2 = .36$. When we repeated the analysis of resting RSA with resting inter-beat and T_{TOT} included as additional covariates, the group difference in RSA remained significant, $B = 0.30$, $t = 3.13$, $p = .003$, $f^2 = .60$ (see Table 2).

Table 2

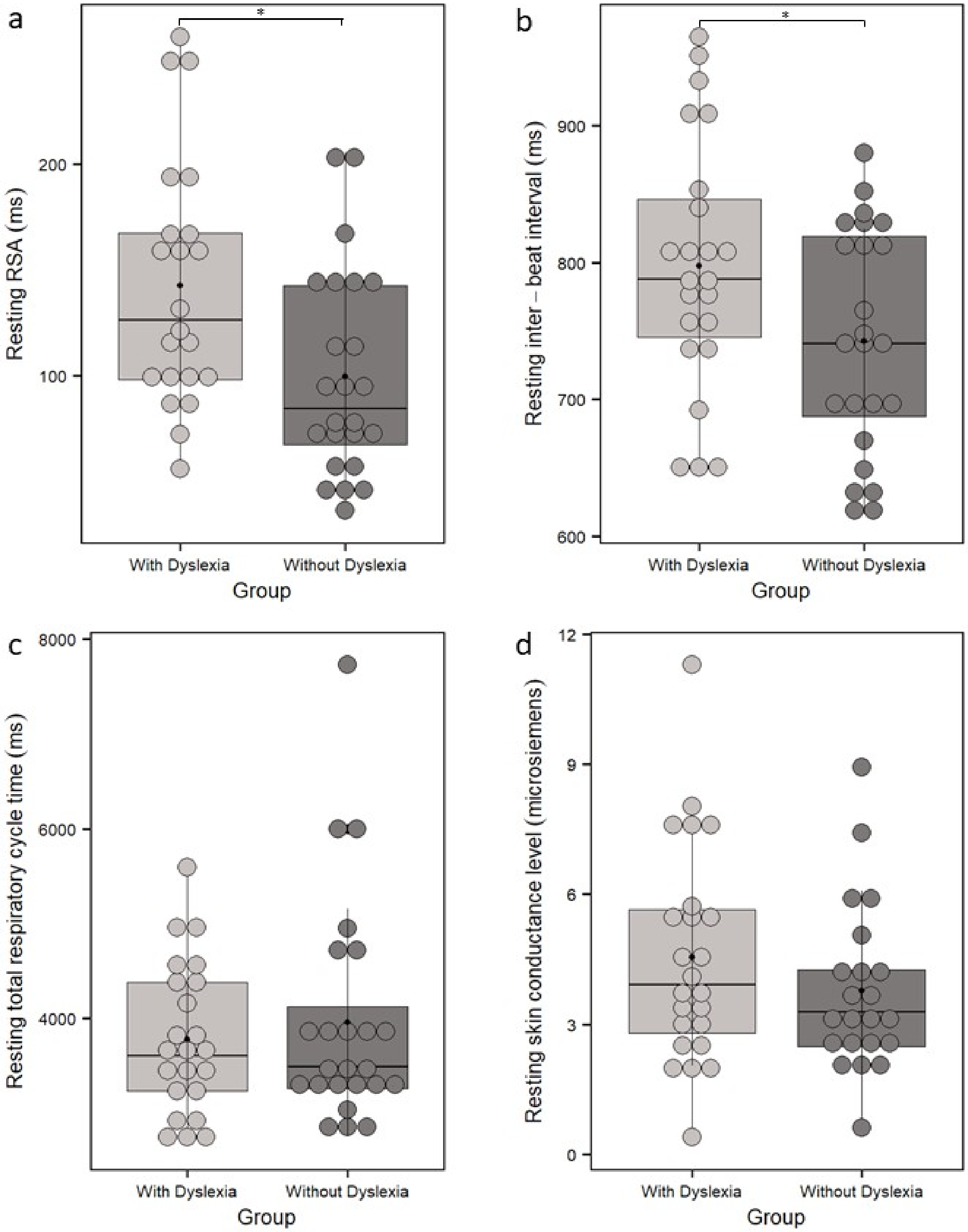
Resting physiology in participants with and without dyslexia. *Ranges, means (M), and standard deviations (SD) are provided for each group.*

Measure	**With Dyslexia**			**Without Dyslexia**		
	Range	***M***	***SD***	**Range**	***M***	***SD***
Resting cardiac inter-beat interval (ms)	644.9 – 964.9	796.8	92.8	615.7 – 879.6	742.3	81.9
Resting T_{TOT} [a] (ms)	2673.8 – 5588.5	3785.1	794.4	2789.0 – 7758.7	3957.6	1196.8
Resting RSA [b] (ms)	55.6 – 260.1	142.5	58.5	35.9– 205.7	99.6	48.8
Resting SCL [c] (microsiemens)	0.4 – 11.3	4.5	2.5	0.6 – 8.9	3.8	1.9

Notes: a) T_{TOT} denotes total respiratory cycle time. b) RSA denotes respiratory sinus arrhythmia. Here, untransformed RSA values are provided for ease of interpretation; however, the data were log transformed prior to statistical analyses. c) SCL denotes skin conductance level.

Figure 1

Children with dyslexia showed higher mean resting (a) respiratory sinus arrhythmia (RSA) and (b) longer inter-beat interval than those without dyslexia. There were no group differences in mean resting (c) total respiratory cycle time (T_{tot}) or (d) skin conductance level. Asterisks indicate a significant difference at *p*<.05. Untransformed RSA is plotted for ease of interpretation.


a
*
Resting RSA (ms)
200
100
With Dyslexia
Without Dyslexia
Group
b
*
Resting inter – beat interval (ms)
900
800
700
600
With Dyslexia
Without Dyslexia
Group
c
Resting total respiratory cycle time (ms)
8000
6000
4000
With Dyslexia
Without Dyslexia
Group
d
Resting skin conductance level (microsiemens)
12
9
6
3
0
With Dyslexia
Without Dyslexia
Group

Empathy Films Task

Physiological Reactivity

The mixed effects models, which were conducted for each physiological channel, revealed that children with dyslexia had greater inter-beat interval reactivity, or greater cardiac deceleration, than those without dyslexia during the empathy films task, $F(1,44) = 5.03$, $p = .030$ (see Table 3 for group-wise descriptive statistics and Figure 2). There was no group by trial interaction on inter-beat interval reactivity, $F(8,362) = 0.86$, $p = .555$, suggesting this effect was comparable across films. Repeating the analysis with T_{TOT} entered as an additional covariate did not change the results; the effect of group on inter-beat interval reactivity remained significant, $F(1,43) = 5.38$, $p = .025$.

The children with dyslexia did not differ from those without dyslexia on T_{TOT} reactivity, $F(1,43) = 0.81$, $p = .374$; RSA reactivity, $F(1,43) \equiv <0.001$, $p = .977$; or SCL reactivity, $F(1,41) = 0.22$, $p = .639$. The group by trial interaction on T_{TOT} reactivity approached, but did not reach, significance, $F(8,333) = 1.90$, $p = .059$, and there was no group by trial interaction on RSA reactivity, $F(8,338) = 0.73$, $p = .668$; or SCL reactivity, $F(8,334) = 0.58$, $p = .795$. Adding T_{TOT} and inter-beat interval reactivity as covariates to the RSA model did not change the results, $F(1,43) = 1.62$, $p = .210$.

Emotional Facial Behavior

The groups displayed comparable levels of total emotional facial behavior in response to the film clips across trials, $F(1,44) = 0.04$, $p = .842$, and there was no group by trial interaction in the mixed effects model, $F(8,44) = 1.13$, $p = .340$. In exploratory analyses, when the individual categories of emotional facial behavior were considered, children with dyslexia displayed more concentration (as indicated by a furrowed brow or by a slight narrowing of the eyes), $B = 2.71$, $t = 2.05$, $p = .046$, $f^2 = .57$, than those without dyslexia (see Supplementary Table 5).

Control Tasks

There were no group differences in familiarity with the film content, $B = 0.02$, $t = 0.09$, $p = .932$, $f^2 = .02$, attention during the task, $B = -0.06$, $t = -0.08$, $p = .933$, $f^2 = .02$, or emotion recognition, $B = -6.97$, $t = -1.84$, $p = .073$, $f^2 = .48$. Compared to participants without dyslexia, those with dyslexia had lower emotion word knowledge, $B = -0.89$, $t = -3.07$, $p = .004$, $f^2 = .79$ (see Table 3).

Table 3

Control tasks and physiological reactivity during the empathy task, in participants with and without dyslexia. Ranges, means (*M*), and standard deviations (*SD*) are provided for each group.

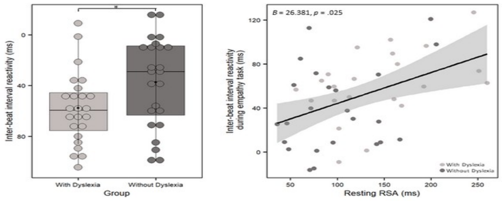
Measure	**With Dyslexia**			**Without Dyslexia**		
	Range	***M***	***SD***	**Range**	***M***	***SD***
Familiarity with film content (%) [a]	0.0 – 44.0	14.8	8.9	0.0 – 38.9	15.3	9.7
Attention during task (%) [b]	88.9 – 100.0	99.5	2.3	88.9 – 100.0	99.5	2.3
Emotion recognition (%) [c]	44.4 – 88.9	66.8	13.5	44.4 – 100	74.4	14.7
Emotion word knowledge [d]	12 – 15	12.9	0.8	12 – 15	13.9	1.2

Inter-beat interval reactivity (ms) [e]	-9.9 – 98.6	55.3	28.6	-16.9 – 97.1	31.9	31.6
T_{TOT} reactivity (ms) [e]	-2256.2 – 38	-919.8	595.4	-2112.3 – 227.6	-601.6	571.4
RSA reactivity (ms) [e]	105.5 – 21.3	31.6	27.4	55.1 – 22.0	-22.9	20.6
SCL reactivity (microsiemens) [e]	-0.2 – 0.1	-0.0	0.1	-0.3 – 0.1	-0.0	0.1
Total emotional facial behavior (units) [f]	0.1 – 3.0	1.2	0.9	0.0 – 4.0	1.1	0.9

Notes: a) Familiarity with film content reflects the percentage of clips participant reports having seen before. b) Attention during task reflects percentage of correctly identified film contents across trials. c) Emotion recognition reflects the percentage of correctly identified emotions across trials. d) Emotion word knowledge reflects total accuracy. Higher scores reflect greater emotion word knowledge, maximum score = 15. e) Measures of physiological reactivity reflect mean change scores from baseline; T_{TOT} indicates total respiratory cycle time, SCL indicates skin conductance level, and RSA indicates respiratory sinus arrhythmia. Here, untransformed RSA values are provided for ease of interpretation though the data were log transformed prior to statistical analyses. f) Total emotional facial behavior reflects the average amount of emotional facial behavior produced by participants while watching the film clips.

Figure 2

Children with dyslexia showed greater cardiac deceleration in response to film clips depicting others' emotions than those without dyslexia (the Y axis has been reversed to aid interpretation).

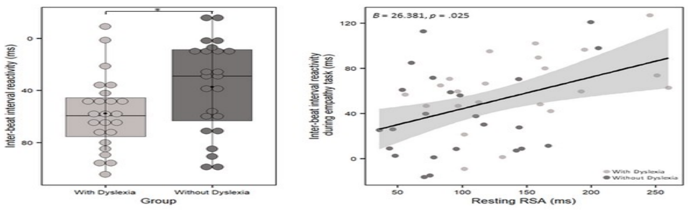


Relationship Between Resting RSA and Autonomic Reactivity During the Empathy Task

Across the sample, resting RSA predicted inter-beat interval reactivity (averaged across trials) during the empathy films task, $B = 26.38$, $t = 2.32$, $p = .025$, $f^2 = .35$ (see Figure 3) such that higher resting RSA was associated with greater cardiac deceleration. Although resting T_{TOT} was not a significant predictor of cardiac deceleration, $B = -0.00$, $t = -0.29$, $p = .771$ $f^2 = .20$, when including resting T_{TOT} as an additional covariate, this result fell to trend level, $B = 29.58$, $t = 1.87$, $p = .070$, $f^2 = .40$. Resting RSA did not predict T_{TOT} reactivity, $B = 386.06$, $t = 1.56$, $p = .126$ $f^2 = .25$, or RSA reactivity, $B = 0.07$, $t = 0.92$, $p = .360$ $f^2 = .04$.

Figure 3

Across the sample, higher resting respiratory sinus arrhythmia (RSA) predicted greater cardiac deceleration (i.e., longer inter-beat intervals) during film-viewing. Asterisks indicate a significant difference at *p*<.05.



4. Discussion

Using a laboratory-based approach, we found children with dyslexia had elevated resting parasympathetic activity as well as enhanced autonomic and behavioral reactions to others' emotions. During the resting baseline, children with dyslexia had higher RSA (indicating higher-heart rate variability) and greater inter-beat interval (indicating slower heart rate) than those without dyslexia. The children with dyslexia also exhibited greater cardiac deceleration during an empathy films task, which, in turn, was associated with higher resting RSA when examined across the sample. Although both groups showed similar mean levels of total emotional facial behavior, exploratory analyses revealed that children with dyslexia displayed greater expressions of concentration (i.e., furrowed brow or narrowed eyes) while watching the film clips than those without dyslexia. Children with dyslexia were equivalent to their peers in recognizing the emotions of characters in film clips, but they had lower emotion word knowledge than those without reading difficulties. Taken together, our results suggest that activity in the parasympathetic nervous system—at rest and perhaps in response to others' emotions—is enhanced in dyslexia.

Activity in the-parasympathetic nervous system fluctuates as people orient, attend, and respond to salient stimuli. In typically developing children, those with greater resting parasympathetic activity are better able to shift and sustain attentional focus (Porges, 1992; Richards & Casey, 1992; Suess et al., 1994). During cognitive tasks, cardiac deceleration occurs when people orient to new information (Abercrombie et al., 2008; Stekelenburg & Van Boxtel., 2002), maintain attention over time (Suess & Porges, 1994; Weber et al., 1994), and process uncertain or ambiguous stimuli (Corcoran et al., 2021). By slowing the heart and fostering facial expressivity, the parasympathetic nervous system is also thought to be critical for social sensitivity and other-oriented empathic responses (Butler & Hodos, 1996; Porges, 1995, 2001; Segerstrom et al., 2012; Thayer & Lane, 2000). Prior studies have shown that children with lower resting heart rate and greater cardiac deceleration in response to others' suffering more often engage in prosocial behaviors (Eisenberg et al., 1989; Zahn-Waxler et al., 1995).

We found that, compared to children without dyslexia, those with dyslexia exhibited greater cardiac deceleration and greater facial expressions of concentration in response to others' emotions. Our findings suggest the children with dyslexia may have been more deeply focused on, or attuned to, the film clips than those without dyslexia. While the accentuated autonomic and behavioral responses of the children with dyslexia during the empathy films task were consistent with an other-oriented emotional empathy response, it did not translate into better emotion recognition as the groups did not differ in their ability to identify the emotions of the characters in the film clips (i.e., there were no differences in cognitive empathy). Using words to label others' (and one's own) affective states depends on one's available emotion vocabulary (e.g., Miller, 2009; Pasalich et al., 2014; Rueda et al., 2014), however, which may be influenced by reading difficulties. In dyslexia, lower emotion word knowledge may make it more challenging for children to label the emotions of others with words despite adequate visceral and motor cues that typically facilitate emotion recognition.

An alternative explanation for our results is that the children with dyslexia exhibited greater cardiac deceleration and greater facial expressions of concentration during film-viewing because they found the task more difficult and exerted greater effort than the children without dyslexia. Although future studies are needed to resolve this issue, several pieces of evidence suggest this explanation is less likely. First, the children with dyslexia in our study did not have disorders of attention (e.g., attention deficit hyperactivity disorder) or spoken language comprehension, which would have made it more challenging for them to attend to and understand the film clips' verbal content. Moreover, language comprehension, sustained attention, and reading comprehension abilities did not correlate with the findings. Second, those with dyslexia performed as well as their peers on the control task that assessed whether they understood the content of the films, which indicates they paid attention to and understood the film clips without trouble. They also did not differ from their peers without reading difficulties in their sustained attention (performance on the flanker task) or in their attention in everyday life (per parent report), which suggests the autonomic and behavioral reactions of the children with dyslexia were not accounted for by difficulties with attention in general (see Supplementary Materials). Third, difficult tasks, particularly those associated with cognitive challenge, are often associated with heart rate increases rather than decreases (Backs & Seljos, 1994; Lenneman & Backs, 2009), as well as suppression of heart rate variability (Byrd et al., 2014; Melis & van Boxtel, 2001; 2007). Thus, it would have been more likely that the children with dyslexia would have shown cardiac acceleration, not deceleration, had they recruited more cognitive resources during the empathy films task. Indeed, in a previous study designed to evoke emotional reactivity (not empathy), we observed cardiac acceleration instead of deceleration in children with and without dyslexia (Sturm et al., 2021). These findings suggest cardiac deceleration in dyslexia is not a generalized response to emotion-inducing film clips but rather may be a specific reaction to film clips depicting people displaying emotions. Altogether, our findings suggest the autonomic and behavioral differences we detected between the groups more likely reflected enhanced social engagement or emotional empathy in the children with dyslexia than heightened effort during this task, but we cannot rule out this possibility entirely. We speculate that elevated parasympathetic activity in dyslexia may promote rapid detection of affective information and sustained attention to social cues, abilities that may yield interpersonal advantages.

The results of the present study extend emerging conceptualizations of emotions and empathy in dyslexia. Our previous work indicated that children with dyslexia had greater emotional facial behavior and larger increases in SCL and respiration rate than those without dyslexia while watching emotionally evocative film clips (Sturm et al., 2021). In that study, children with dyslexia who were more facially expressive had better social skills. Social relationships are complex, and it is likely that interpersonally skilled individuals are not only sensitive to affective cues but are also adept at managing their emotions and attending to others. In our prior study, the film clips participants viewed were selected to elicit strong emotions, and participants' reactions suggested sympathetic nervous system activity increased during film-viewing. Here, when viewing film clips selected for their social content (i.e., depicting people displaying emotions), the children with dyslexia had greater cardiac deceleration than their peers. Although additional research is needed, these initial studies suggest outflow from both the sympathetic and parasympathetic branches of the autonomic nervous system may be enhanced in dyslexia. Our studies suggest that while children with dyslexia may be more reactive to affective cues in general, they may also be better equipped to maintain an other-oriented stance that allows them to notice and respond to those around them. Together, fine-tuned functioning in the sympathetic and parasympathetic nervous systems in dyslexia may promote nuanced empathic responding and skilled social behavior.

Many unanswered questions remain regarding the mechanisms underlying the enhanced emotional reactions to social stimuli that we detected in dyslexia. One possibility is that persistent difficulties with reading are a chronic stressor that impacts the development of brain systems that support emotions and social behavior just as other forms of early-life adversity affect these systems (Krugers et al., 2017; Teicher & Samson, 2016; Teicher et al., 2016). Children who have experienced significant adverse events, for example, exhibit enhanced neural activity in emotion-relevant structures in response to social exclusion (van Harmelen et al., 2014) and emotional faces (van Harmelen et al., 2013). Childhood adversity, however, is most often (Daches et al., 2017; Rigterink et al., 2010; Miskovic, Schmidt et al., 2009), but not always (Johnson et al., 2017, Winzeler et al., 2017), associated with lowered, not elevated, parasympathetic activity, and it is unclear whether academic struggles would affect emotion systems in a similar way as other forms of early life adversity. Another possibility is that enhanced emotional and social sensitivity in dyslexia develops alongside reading difficulties and reflects differences in brain organization. Prior to reading instruction, children at familial risk of dyslexia have organizational differences in brain networks that support reading (Black et al., 2012; Qi et al., 2016; Raschle et al., 2011; Vandermosten et al., 2015). Whether there are structural or functional differences in other brain networks, such as those that support emotions, in those at risk for reading challenges is not well understood but could help to explain how individuals who have difficulty reading may also be predisposed for interpersonal strengths.

There are several important limitations of this work to consider. First, we did not find evidence that children with dyslexia had enhanced facial mimicry of the characters in the film clips, a common feature of emotional empathy. An empathic response, however, may not always be characterized by mirroring the affective state of the other (Fischer & Hess, 2017; Wróbel & Imbir, 2019). Sharing another's emotions, and negative emotions in particular, may escalate distress and hinder prosocial actions (Decety, 2010; Eisenberg et al., 1994; Hatfield et al., 1993) while a reassuring smile in response may signal understanding and compassion to someone who is suffering (Oveis et al., 2010). Our coding system was not fine-grained enough to distinguish among subtle differences in facial expression, such as different types of smiles (Neidenthal et al., 2010), however. Indeed, of the two analyses of facial behavior employed, neither may be optimal, and both have associated limitations. One the one hand, averaging across different behaviors may obscure differences between emotions, and on the other, examining individual behaviors risks inflation of the false discovery rate. Future studies are needed to explore this issue in more detail.

Second, research needs to be conducted to quantify the influence of other variables that can affect autonomic activity, such as tidal volume and fitness and activity levels on the group differences observed (Grossman & Taylor, 2007), as well as further explore the role of sex and age in larger cohorts. In addition, we did not find a group difference in RSA reactivity during film-viewing, which may be due to the relatively short period during which RSA was measured in each trial (Berntson et al., 1997; Malik et al., 1996). Although cardiac deceleration can also reflect increased vagal inhibition of the heart (Berntson et al., 1993; Danielsen et al., 1989; Holstege, 1989; Onai et al., 1987; Richards & Casey, 1991), further studies of RSA and its relation to cardiac and respiratory influences are warranted.

Third, most of the children with dyslexia in the present study attend specialist schools for children with learning differences, where they receive a considerable amount of support. The enhanced responses to emotional stimuli they displayed, therefore, may be emblematic of children with dyslexia who are relatively well-supported. Enhanced emotional and social responding may represent a double-edged sword, both increasing social skill but also introducing a vulnerability to affective symptoms, such as anxiety (Sturm et al., 2021). Future work will need to address how early life experiences and lack of social and academic support influence emotions in dyslexia as early interventions in vulnerable children will be of paramount importance in shaping their developmental trajectories (Daskalakis et al., 2013).

To date, most research on dyslexia has focused on reading. While instrumental in advancing our understanding of the linguistic profile of children with dyslexia and helping to inform academic interventions for these children, this narrow focus may have overlooked other associated features of the condition. The present study builds on emerging research and helps to extend our understanding of emotions in dyslexia. In addition to the well-documented reading challenges that children with dyslexia face, our results suggest some may demonstrate strengths in socioemotional abilities that reflect underlying differences in physiology and behavior.

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