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ORIGINAL PAPER

Exploring Subtypes of Repetitive Behavior in Children with Autism Through Functional Analysis and Wearable Technology: a Pilot Biobehavioral Assessment

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Abstract

Objectives Prior research has established assessment methodologies, such as functional analysis to identify specific contexts in which restricted and repetitive behavior (RRB) occurs, and measures of heart rate variability (HRV) to index the level of autonomic arousal in individuals with autism spectrum disorder (ASD). Yet, a gap remains in integrating multiple assessment methodologies to examine the complex underlying mechanisms of RRB. This study piloted a multi-disciplinary approach to assess both the functional behavioral and neurophysiological factors that may underlie occurrences of RRB. The study (a) evaluated the effect of a modified functional analysis protocol on delineating functional subtypes of RRB and (b) explored the effect of using a wearable technology within a functional analysis on identifying the relationship between RRB and HRV.

Method A single-case alternating treatment design was used to randomly alternate noncontingent low-stimulation and high-stimulation conditions in a modified functional analysis protocol. Simultaneous measurement of RRB and HRV was obtained through direct behavioral observations and a wristband that collects blood volume pulse, respectively. Visual analysis of time series data was used to determine the functional subtypes of RRB, and nonparametric correlational analyses were conducted to determine the association between HRV and RRB.

Results Findings from a sample of six participants suggest preliminary effectiveness of the assessment protocol in identifying subtypes of RRB and a significant correlation between HRV and RRB.

Conclusions This study demonstrates the potential effect and usability of a wearable technology-aided biobehavioral approach to assess RRB and HRV in individuals with ASD.

Keywords Autism · Stereotypy · Autonomic arousal · Functional analysis · Wearable technology

Engaging in restricted and repetitive behaviors (RRBs) is one of the core diagnostic features of autism spectrum disorder (ASD). RRBs include stereotyped motor movements or speech, ritualistic patterns of verbal or nonverbal behavior, highly restricted interests, and hyper- or hypo-reactivity to sensory input (American Psychiatric Association, 2013). RRBs can be identified before 2 years of age (Fakhoury, 2015; Guthrie et al., 2013) and tend to persist and increase in severity over time (Guthrie et al., 2013; Matson et al., 2010). While some RRBs may not interfere with the daily functioning and well-being of autistic individuals, certain frequent and severe RRBs may be the cause of increased physical risks, social exclusion, more restrictive educational placement, and long-term use of psychotropic medications (Matson et al., 2010).

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From a behavior analytic perspective, RRBs are operant behaviors that may be maintained by social or nonsocial consequences that follow the behavior, including (a) social positive reinforcement, (b) social negative reinforcement, (c) automatic positive reinforcement, and (d) automatic negative reinforcement (Durand & Carr, 1987; Kennedy et al., 2000; Rapp & Vollmer, 2005). These variables that influence the occurrence of a target behavior can be identified through a functional analysis (FA), which identifies variables that maintain the target behavior through analyzing its relationship with environmental events (Hanley et al., 2003; Iwata et al., 1994). In the initial FA model described by Iwata et al. (1994), participants are repeatedly exposed to four conditions, including (a) a social positive reinforcement condition where social attention is withheld until target behavior occurs and then provided contingent on every occurrence of target behavior; (b) a social negative reinforcement condition where task demands are presented until target behavior occurs and then removed contingent on every occurrence of target behavior; (c) an automatic reinforcement condition where the participant is alone without any social contingencies; and (d) a control condition, where the participant is given unrestricted access to unstructured play activities with moderate social attention and no task demands regardless of the occurrence of target behavior (Iwata et al., 1994). Typically, a comparatively higher rate of target behavior in one condition indicates that the behavior is maintained by the reinforcer accessible in that condition (Roane et al., 2013).

There have been numerous studies targeting the reduction of RRBs in individuals with ASD over the past few decades based on the science of applied behavior analysis (ABA; DiGennaro Reed et al., 2012). However, the nonsocial function of repetitive behavior poses a challenge in the design of intervention for automatically reinforced behavior as the variables maintaining the behavior cannot be controlled by another individual. Yet, the literature has established that automatic reinforcement is the most prevalent function of stereotypic behaviors (Beavers et al., 2013; Rapp & Vollmer, 2005). Studies that attempted to address repetitive behaviors maintained by automatic reinforcement have primarily relied on procedures that manipulate social consequences, such as tangible objects or attention, or punishment procedures that rapidly reduce stereotypic behavior (Rapp & Vollmer, 2005). When treatments are aimed at suppressing specific forms of RRBs rather than addressing the function, they often lead to increases in other forms of RRBs not targeted in the treatment (Lanovaz & Sladeczek, 2012). The ability to effectively address RRBs through behavioral assessment and intervention remains a gap in ABA research.

In the neurophysiological literature, the presence of RRBs in ASD has been conceptualized as behaviors caused by biological mechanisms associated with atypical neural development and functions in individuals diagnosed with ASD. For example, the polyvagal theory proposes that ASD symptoms can be attributed to the dysregulation of the autonomic nervous system (ANS; Porges, 2003, 2005, 2007). The ANS is part of the peripheral nervous system and serves to regulate functional states of visceral organs and maintain homeostasis. With respect to ASD symptoms, the polyvagal theory postulates that the physiological state (i.e., autonomic arousal) impacts the capacity of an individual in the engagement of social communicative behavior, which is central to the difficulties that autistic individuals have (Porges, 2007). Neurotypical individuals control the extent of vagal influence in a manner that allows for effective pacing of the heart and thus more efficient regulation of physiological arousal. On the other hand, the ANS in ASD is compromised, and the resulting inefficient modulation of autonomic arousal manifests as atypical characteristics in the domains of social communication and RRBs (Liss et al., 2006; Mathersul et al., 2013; Porges, 2003, 2007).

Prior research has shown that compared to neurotypical individuals, autistic individuals tend to be over-aroused or under-aroused even at resting state when environmental stimuli evoke minimal stress (Anderson & Colombo, 2009; Mathersul et al., 2013). Studies have also shown that autistic individuals regulate their arousal differently in response to different types or intensities of sensory stimuli in their daily environment, leading to responses that range from under- to over-reactivity (Boyd et al., 2010; Liss et al., 2006).

Achieving reliable quantification of behavior through utilizing operationalized definitions of behavior and accurate measurement systems is one of the core dimensions of ABA (Baer et al., 1968). In the field of ABA, behaviors are commonly measured by event recording systems through direct observations (Cooper et al., 2020), which measure the frequency a behavior over a specific period and provide a direct measure of observable behavior (Lane & Ledford, 2014). Behavioral data obtained from direct observations offer an opportunity for researchers to identify specific environmental conditions in which the behavior occurs rather than making inferences regarding the context based on indirect observations or perceptions (i.e., caregiver interviews, caregiver questionnaires, self-reports). However, it remains a major limitation of direct observations that only external behaviors observable to another person can be recorded.

Autonomic arousal, an internal indicator of neurophysiological activity, can be measured through changes in pupil size, electrodermal activity, and heart rate variability (HRV), all of which are influenced by ANS activity (Wass et al., 2015). These indices have been utilized in ASD samples extensively to identify the relationship between autonomic arousal and phenotypical features of ASD (Lydon et al., 2016). In particular, HRV is recognized as a relatively direct indicator of ANS functioning that is sensitive across a range of physiological arousal (Friedman, 2007; Karemaker, 2017; Wass et al., 2015). For example, a study conducted by Condy and colleagues (2017) found significant associations between lower HRV and more severe social communication impairments and RRB (Condy et al., 2017).

Similar with most empirical research in the psychological and biobehavioral literature, behavioral symptoms of ASD are often measured through indirect measures such as caregiver report questionnaires (e.g., Matsushima et al., 2016) or behavior rating checklists based on perceived intensity or severity (e.g., Woodard et al., 2012). While there is broad empirical support for the use of standardized rating scales to index behavioral symptoms of ASD (e.g., sensory profile, social communication questionnaire), it is difficult to interpret the results of these indirect behavioral measures in the exact context in which physiological arousal is measured due to time discrepancy between the behavioral and physiological measures.

To address this gap, a small but emerging body of research has begun to develop multi-method assessments to collect both physiological and direct behavioral data as indicators of arousal and challenging behavior (Lydon et al. 2013; Moskowitz et al., 2013, 2017). In these studies, the collection of direct behavioral data involved operational definitions of the target behavior and quantitative measurement of the target behavior based on direct observation. For example, Moskowitz et al. (2017) measured HRV along with external behavior throughout the baseline and intervention of an intervention package involving cognitive behavioral therapy (Sturmey, 2004) and positive behavior supports (Carr et al., 2002; Dunlap & Carr, 2009) to determine if there was an association between changes in anxious behavior (e.g., crying, clinging, repetitive questions) and arousal. Study results showed immediate changes in external behavior but not corresponding changes in HRV.

Although research related to the origin of and measurement of RRB has grown across various disciplines, the work on RRB has mostly been done within each field and in isolation from other fields (Leekam et al., 2011). Leveraging our understanding of the behavioral characteristics of ASD across sciences may provide an additional lens for examining the mechanisms of ASD symptoms. The current study aimed to contribute to the emerging research by piloting a multi-method assessment approach that integrates techniques across the ABA and neurophysiology disciplines to measure both external behavior and autonomic arousal in individuals with ASD at the same time. In this study, HRV and duration of RRB were recorded simultaneously in children with ASD within natural environments. This study sought to address the following research questions: (a) What is the effect of a modified FA protocol in delineating more specific subtypes of automatically reinforced RRB (i.e., automatic positive reinforcement, automatic negative reinforcement, mixed automatic reinforcement)? (b) Is there an association between HRV and RRB when they are measured simultaneously in children with ASD during FA conditions without social contingencies?

Method

Participants

Following approved procedures from the Institutional Review Board, study participants were recruited from two private centers that provided intensive ABA services to children diagnosed with ASD in suburban Midwestern United States. Potential participants who met the following inclusion criteria were identified via referrals from center administrators and supervisory staff: (a) presence of medical or educational diagnoses of ASD made by independent parties (e.g., physicians, psychologists), (b) age between 3 to 12 years old, and (c) daily occurrences of observable RRB such as vocal or motor stereotypic behaviors. Upon parental authorization of the release of their child's health information, the researcher reviewed each participant's clinical records to confirm the presence of an ASD diagnosis. Table 1 shows an overview of participant characteristics including age, sex, race, or ethnicity; disability or medical diagnosis; medication; the use of augmentative and alternative communication (AAC); areas of need in adaptive functioning; and the topographies of RRB measured. The ages of participants included ranged from 4 to 7 years old. Two of the participants had additional diagnoses in addition to ASD, and both were taking medication at the time of the study. Three out of six participants used a speech-generating device or American Sign Language as their AAC. Three of the participants demonstrated primarily vocal stereotypy, while the other three participants demonstrated both vocal and motor stereotypy.

Procedure

Setting

Study sessions were implemented in vacant rooms at the centers. Each room included at least two tables and two chairs, with minimal other mobile furniture. All objects that were not relevant to the study were stored out of reach on a shelf or in closed containers. A wireless speaker was used to play noise during the noise condition of the study sessions. Due to increased health risks caused by the COVID-19 pandemic, the researcher led and monitored all study sessions remotely via video conferencing software to minimize in-person interactions with clinic staff and study participants. A clinic staff who worked one-on-one with each participant

Table 1 Participant demographics and behavior description

Name	Age; sex; race/ethnicity	Disability/medical diagnosis	Medication	AAC	Examples of adaptive skill targets	Topographies of repetitive behavior
Cassie	6; female; White	ASD; sensory disturbance; developmental delay; seizure disorder (nocturnal epilepsy)	Clobazam, famotidine, keppra, levetiracetam, prednisone	-	Washing hands, dressing and grooming, requesting for items	Scripting of songs or dialogues from animated shows; nonspeech vocalizations; body rocking; hand flapping
Greta	4; female; White	ASD	-	ASL and SGD	Grooming, requesting for preferred activities, imitating play behaviors	Scripting of phrases from songs or animated shows; nonspeech vocalizations
Roger	4; male; White	ASD; language impairment; epilepsy; global developmental delay; seizure disorder	Keppra	SGD	Unpacking food, toileting, imitating modeled physical movements	Nonspeech vocalizations; body spinning; hand flapping; hopping; pacing; object tapping or knocking
Marc	7; male; Hispanic	ASD	-	-	Grooming, drinking without spilling, requesting help	Out-of-context speech; scripting of songs or dialogues; nonspeech vocalizations
Griffin	7; male; White	ASD	-	-	Eating with utensils, requesting for items, following instructions	Out-of-context speech; nonspeech vocalizations.
Aubrey	5; female; White	ASD	-	SGD	Dressing, toileting, requesting for items	Scripting of songs or dialogues; nonspeech vocalizations; object mouthing; hand flapping; shoulder tapping

AAC, augmentative and alternative communication; *ASD*, autism spectrum disorder; *ASL*, American Sign Language; *SGD*, speech-generating device. Participant names are pseudonyms. Participant ages are ages at study enrollment implemented all study sessions. The researcher, a board-certified behavior analyst® and doctoral student in Special Education, trained each clinic staff in implementing the study sessions and provided live instructions and feedback via video conference (i.e., Zoom™, WebEx™) using a tablet during all study sessions. The staff used a video camera or tablet to video record each participant's behavior in all study sessions. Using these recorded videos, data on target repetitive behavior were extracted post-session through a software, MOOSES™ (Multi-Option Observation System for Experimental Studies; Tapp et al., 1995). All participants wore an Empatica E4 wristband during study sessions to acquire data for HRV analysis.

Experimental Design

A single-case alternating treatment design (Barlow & Hayes, 1979) without baseline was used to compare the effects of two conditions (i.e., silent and noise) of the modified FA on the dependent variables. The two conditions were alternated within each day for majority of the days when study sessions were implemented. To minimize potential sequence effects, the alternating sequence was randomly determined with no more than two consecutive sessions of the same condition. For each participant, an average of two modified FA sessions was implemented per day, across 3 to 5 days a week. On some of the days, one or three sessions were implemented based on the availability of the child participant and the clinic staff on a particular day. The alternation between conditions sometimes occurred across days instead of within a day if only one session was implemented on a day.

The purpose of the silent condition was to simulate a low-stimulation environment and evoke behavior maintained by automatic access to stimulation; the purpose of the noise condition was to simulate a high-stimulation environment and evoke behavior maintained by automatic escape from stimulation. If a participant engaged in higher levels of target repetitive behavior in the silent relative to the noise condition, the behavior was hypothesized to have an *automatic positive reinforcement* function. If a participant engaged in higher levels of target repetitive behavior in the noise relative to the silent condition, the behavior was hypothesized to have an *automatic negative reinforcement* function. If a participant engaged in similar levels of target repetitive behavior across the silent and noise conditions, the behavior was hypothesized to have a *mixed automatic reinforcement* function. If a participant engaged in minimal levels of target repetitive behavior in both conditions, the behavior was hypothesized to have a *social reinforcement* function instead of an automatic reinforcement function. An illustration of the study design and hypothesized subtypes based on the modified FA outcome is shown in Fig. 1.

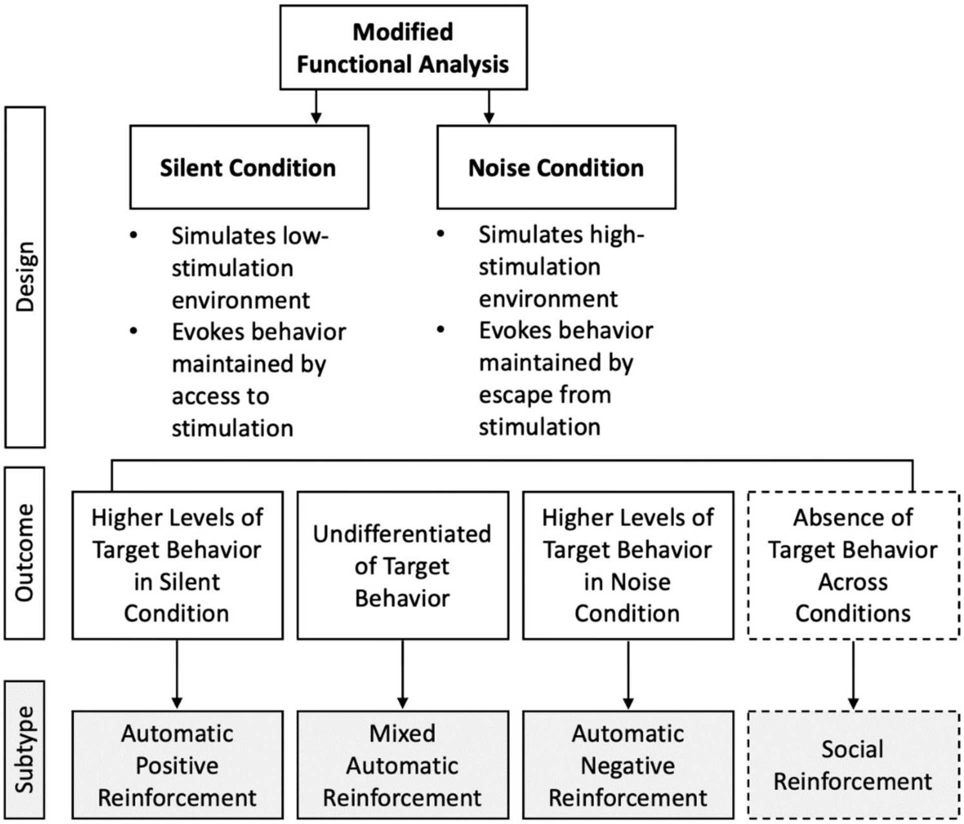

Fig. 1 Study design and hypothesized outcomes with corresponding functional subtypes

Screening Interview and Assessment

A brief functional assessment interview was conducted based on a protocol adapted from the open-ended functional assessment interview (Hanley, 2012). The researcher adapted the questions to specifically identify information related to each participant's background information, target behavior, harmful behavior if any, situations that typically evoke the target behavior, and consequences that typically follow the target behavior. The researcher conducted the interview with the supervising clinic staff of each of the eight initial participants who consented to participate in the study. Information obtained from the interview was used to develop operational definitions of each participant's target RRBs and determine if automatic reinforcement was a probable function of the target behaviors. Based on the interview results, all eight participants were hypothesized to have automatically reinforced RRBs. However, two participants withdrew from the study after the interview as one participant did not agree to wear the digital wristband for subsequent assessments and another participant had a schedule change that conflicted with study participation. As a result, only six remaining participants continued to participate in subsequent study procedures.

Following the interview, a screening observational assessment based on the protocol described in Querim et al. (2013) was implemented with the remaining six participants to confirm if the function of each participant's target repetitive behavior was automatic reinforcement. Each observation session was 5 min in duration. Prior to the start of each session, the researcher asked the clinic staff to put away all instructional materials and toys in the room, if any, and to ensure that a speech-generating device was present for participants who needed it as a primary means of communication. Then, the clinic staff assisted each participant in wearing the digital wristband and video recorded the participant from a distance throughout the session. The clinic staff was also instructed to withhold social interaction with the participant and ignore all behaviors unless the participant engaged in severely harmful self-injurious behavior (e.g., head hitting against a hard surface). If the participant attempted to take the wristband off, the clinic staff was asked to physically block each attempt without speaking to the participant.

At least five screening assessment sessions were implemented with each participant, or until a predictive pattern of data was obtained. Persistent levels of RRBs in the screening assessment would confirm the hypothesis that the behaviors were maintained by automatic reinforcement, in which case the participant would enter the experimental phase of the study, the modified FA. All six participants engaged in persistent levels of RRBs across five to eight sessions and were eligible to participate in the experimental phase of the study.

Modified Functional Analysis

A modified FA adapted from the traditional FA (Iwata, et al., 1994) was conducted with participants whose behavior data demonstrate an automatic reinforcement function based on the results of the screening assessment. In this study, the ignore condition from Iwata, et al. (1994) was adopted and shortened in duration (from 15 to 5 min). While research has documented an approximate 7% loss in accuracy of assessment results when session duration is reduced from 15 to 5 min, studies that utilized 5-min duration in FAs increased threefold between 2003 and 2013 to increase efficiency (Beavers et al., 2013). Considering the increased efficiency relative to the minimal reduction in accuracy, as well as the anticipated exposure to loud noise across multiple sessions in this study, 5 min was selected as the session duration to enhance efficiency and reduce the aversiveness of the study sessions.

Two conditions were randomly alternated in the modified FA: (a) silent (low stimulation) and (b) noise (high stimulation). Each session was 5 min in duration. Procedures in the silent condition of the modified FA were identical to the procedures in the screening assessment (steps 1–10 in Table 2), while the procedures in the noise condition of the modified FA included the same procedures plus two additional steps (steps 12–13 in Table 2). These additional steps were placing the speaker out of reach to the participant and presenting noncontingent, intermittent white noise throughout the session. The presentation of noise was independent of the occurrence or nonoccurrence of the target behaviors. In the noise condition, intermittent white noise was presented at 50–60 dB as an auditory stimulus to imitate the noise level in a classroom with ongoing activities, loud voices, and background music (Russo et al., 2018), which was similar to the average volume in a typical classroom with regular activities and talking (Dockrell & Shield, 2006). Presenting sounds at or below 85 dB for less than 20 min a day was in adherence with the World Health Organization guidelines on safe exposure levels for noise (World Health Organization, 2015). A nonsocial auditory stimulus (i.e., white noise) instead of a social auditory stimulus (e.g., speech, music) was selected to eliminate the potential confound of social variables in the modified FA. Other forms of stimuli, such as visual or tactile, were not used in this study to avoid the delivery of social contingencies needed to ensure that participants attended to visual or tactile stimuli (e.g., "look at this", "play with this").

For Aubrey, an additional phase of the modified FA (i.e., with access to toy) was introduced as the clinic staff reported based on informal observations that Aubrey's repetitive behavior tended to occur at a higher frequency when she engaged with preferred toys or items, which were frequently accessible in her natural setting. This phase was designed to

Table 2 Study session procedural fidelity checklist

Study procedures
Steps for screening assessment and all conditions of FA
1. Participant wears a wristband throughout session
2. Participant is video recorded throughout session
3. Staff stays in the same room as participant and maintains distance (approx. 6 ft)
4. Instructional materials are absent or out of reach
5. Toys are absent or out of reach
6. Speech generating device is present, if applicable
7. Staff ignores all mands
8. Staff ignores all target behaviors
9. If participant attempts to take wristband off or reach for other items, staff blocks attempt without providing additional attention
10. Session is ended when duration reaches 5 min or when a termination criterion is met
Additional steps for noise condition of FA
11. Speaker is placed out of reach to participant
12. Intermittent noise is played for 5 min
Additional steps for toy access condition of FA
13. A preferred item/toy is presented at start of session

Each step can be marked as correct, incorrect, or not applicable. *FA*, functional analysis. Termination criteria were included to allow staff to intervene if they observed severely harmful self-injurious behavior (e.g., head banging against a hard surface)

simulate a more natural environment for Aubrey during the study sessions, in which the clinic staff presented a preferred item (e.g., glitter slime, princess pictures, stuffed doll) at the beginning of each session and told Aubrey “You can play with this if you want” (steps 13 in Table 2).

Measures

Dependent Variables

The primary dependent variable was the total duration of target behavior occurrences within each 5-min session. The target repetitive behavior was measured in seconds through the MOOSES™ software (Tapp et al., 1995). In this software, the onset and offset of repetitive behavior could be recorded with 1 s as the smallest unit. The total duration per session was the sum of the duration of each occurrence of the target behavior.

The secondary dependent variable was HRV within each 5-min FA session. An Empatica E4 wristband was used to collect photoplethysmography (PPG) signal, which is a measure of blood volume pulse (Allen, 2007). The Empatica E4 wristband has a wristband length of 110–190 mm, a weight of 25 g, and a cost of USD$1275. Recent research that investigated the validity of the E4 wristband in measuring heart rate suggests that HRV data obtained from the E4 wristband is comparable to the gold standard electrocardiogram device (Milstein & Gordon, 2020; Stuyck et al., 2022). The PPG data were processed and converted into *R*-waves (i.e., visual representation of heartbeat cycles) using Kubios HRV software (Tarvainen et al., 2014). Within the software, a medium threshold of 0.25 s for artifact correction was selected to identify incorrect inter-beat intervals compared to the local average in each session. Subsequently, the artifact segments were replaced with interpolated values using cubic spline interpolation. Root mean square of successive RR interval differences (RMSSD) was obtained as an index of HRV within each 5-min-modified FA session (Appelhans & Luecken, 2006; Silvetti et al., 2001). RMSSD is a temporal measure of HRV that has been documented to be relatively reliable for short-term recordings of heart rate (i.e., 5 min or less), less influenced by respiration, and more representative of the parasympathetic nervous system (Shaffer & Ginsberg, 2017).

Interobserver Agreement

Interobserver agreement (IOA) data for the primary dependent variable was obtained across two independent observers for at least 33% of sessions (i.e., one randomly selected session out of three sessions) in each condition of the modified FA for each participant. The primary observer was the researcher and the secondary observers included doctoral students in Special Education who were trained in measurement systems of single-case research methods. Primary and secondary observers watched the video recordings of study sessions independently at different times and collected target behavior data based on written definitions each participant’s target behavior. IOA between two observers was calculated through second-by-second comparisons (MacLean et al., 1985; Mudford et al., 2009). A mean IOA across sessions was calculated for the screening assessment and within each condition of the functional analysis for each participant. Overall, the mean IOA was 92% (range = 78–100) for Cassie, 83% (range = 74–92) for Greta, 86% (range = 79–100) for Roger, 82% (range = 70–90) for Marc, 81% (range = 77–86) for Griffin, and 96% (range = 82–100) for Aubrey.

Procedural Fidelity

Procedural fidelity data were collected by two independent observers through evaluating video recordings of study sessions against a researcher-developed checklist for at least 33% of sessions across the screening assessment and each condition of the modified FA. In addition, IOA of procedural fidelity was obtained through calculating the item-by-item agreement between two observers. Primary observers included doctoral students in Special Education (not the researcher), and secondary observers included undergraduate research assistants in Special Education or Speech and Language Hearing Sciences programs. Each of the 13 steps in the checklist could be scored as *correct*, *incorrect*, or *not applicable*. Each step had to be implemented correctly throughout a session to be scored as *correct*. If a step was implemented incorrectly at any point in time during a session, the step was scored as *incorrect*. Procedural fidelity was calculated as a percentage of correct steps. The mean procedural fidelity across sessions was 98% (range = 88–100%; IOA = 100%) for Cassie, 98% for Greta (range = 88–100%; IOA = 91%), 97% (range = 88–100%; IOA = 100%) for Roger, 99% (range = 88–100%; IOA = 98%) for Marc, 99% (range = 86–100%; IOA = 96%) for Griffin, and 100% (IOA = 100%) for Aubrey.

Data Analyses

The repetitive behavior data collected through the modified FA were evaluated using visual analysis to determine the specific functional subtype. A nonparametric single-case effect size NAP (Parker & Vannest, 2009) was used to supplement the visual analysis.

The HRV data collected through the digital wristband were aggregated across sessions, and a correlation analysis between the primary and secondary dependent variables, duration of RRB and level of HRV, was conducted to determine the correlation. A Wilcoxon rank-sum test (Wilcoxon, 1945) was used to identify any significant difference in HRV between the modified FA conditions.

Results

Automatic Reinforcement Subtypes

Results of the modified FA are displayed in Fig. 2. For Cassie, the mean duration of her target repetitive behavior was 88 s (range = 26–176) in the silent condition and 40 s (range = 7–125) in the noise condition. She showed moderate levels of target behavior (vocal and motor stereotypy) in the silent condition, and low levels of target behavior in the noise condition were initially observed from session 1 to 7, with no overlap between the two conditions. A medication change occurred before session 3, but no observable changes were observed in either condition in the sessions immediately following the medication change. Beginning from session 8, increased variability was observed across both conditions, resulting in substantial overlap and lack of clear differentiation in the duration of target behavior. However, over the last six sessions (sessions 19 to 24) of the modified FA, Cassie demonstrated low and stable levels of target behavior in the noise condition and moderate and stable levels of target behavior in the silent condition. While staff changes occurred frequently over sessions 17 and 24 due to reasons unrelated to the study, these changes did not appear to visibly influence Cassie's levels of target behavior. NAP effect across the two conditions was 0.826, indicating medium overlap. Overall, Cassie's result indicated that the function of her target behavior was automatic positive reinforcement.

For Greta, levels of the target repetitive behavior (vocal stereotypy) were relatively low and stable (*M* = 58, range = 23–109) in the noise condition, while levels in the silent condition were moderate with some variability (*M* = 130, range = 47–215). A clear differentiation with minimal overlap in levels of target behavior between the silent and noise conditions was observed, with relatively higher levels of target behavior in the silent condition than in the noise condition. NAP effect across the two conditions was 0.889, indicating medium overlap. The modified FA result over 17 sessions suggested that the function of Greta's target behavior was automatic positive reinforcement.

For Roger, moderate to high levels of target behavior (vocal and motor stereotypy) were observed in the silent condition (*M* = 102, range = 33–199) and the noise condition (*M* = 71, range = 0–232) within the first five sessions of the modified FA. A 1-month break occurred between sessions 5 and 6 when Roger did not receive services at the center due to a decrease in the center's service capacity caused by the COVID-19 pandemic. Roger resumed study participation after he returned to the center for treatment. Upon his return, a change in staff occurred, and the study session time changed from 10:00 a.m. to 1:00 p.m. After his return from the break, large decreases in the target behavior were observed across both silent (*M* = 62, range = 33–76) and noise (*M* = 20, range = 0–48) conditions. Relatively higher levels of target behavior were observed in the silent condition than in the noise condition, with a clear separation of data between the two conditions. NAP effect across the two conditions was 0.694 across all 14

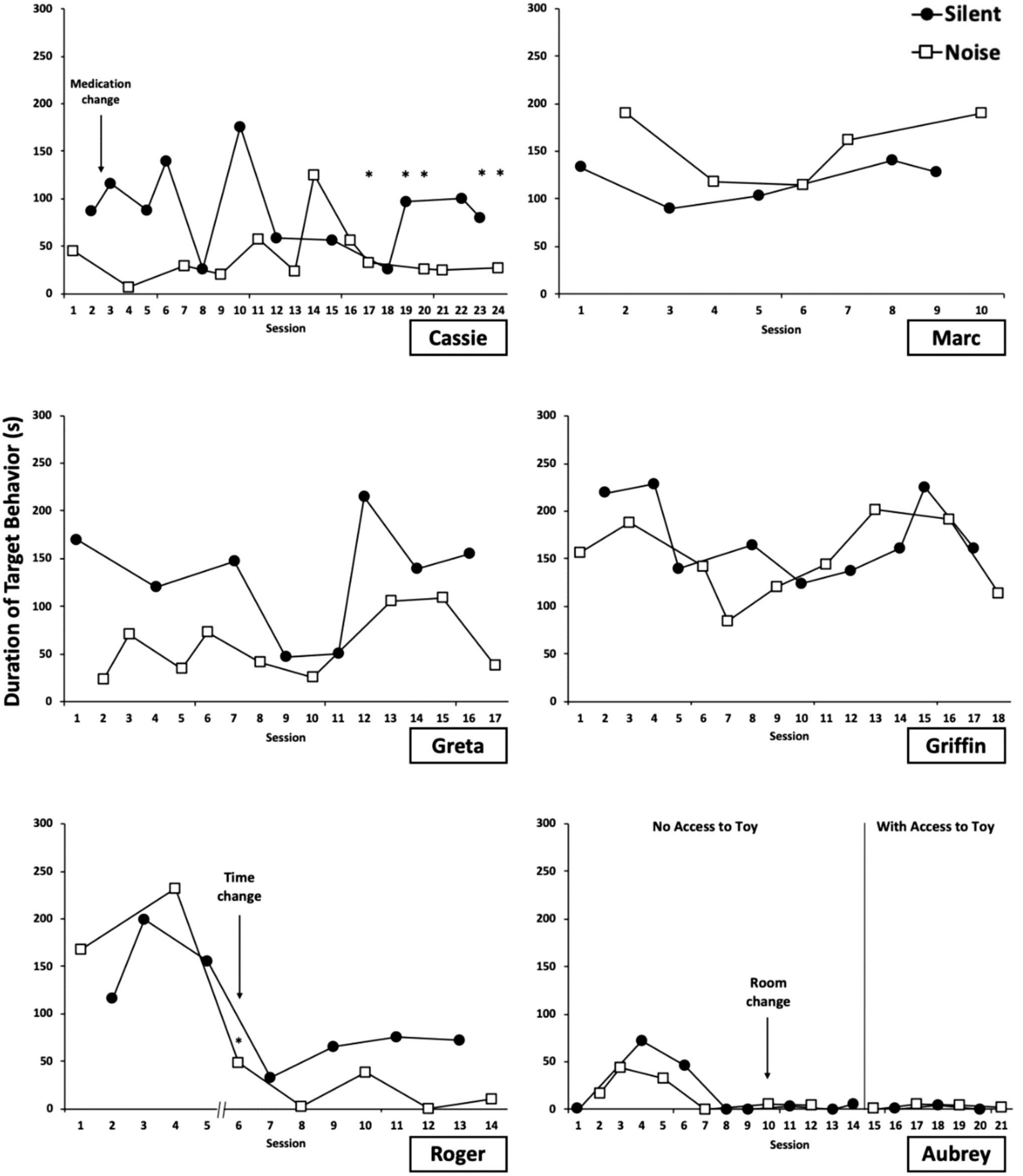

Fig. 2 Results of the modified functional analysis for six participants. Asterisks (*) indicate sessions with a change in staff who implemented the session. For Cassie, a medication change occurred before session 3, and staff changes occurred in sessions 17, 19, 20, 23, and 24. For Roger, a 1-month break occurred between sessions 5 and 6, a staff change occurred in session 6, and a time change (from morning to afternoon) occurred beginning from session 6. For Aubrey, study sessions were implemented in a different clinic room beginning from session 10

sessions, indicating medium overlap. Roger's result indicated that the function of his target behavior was automatic positive reinforcement.

For Marc, the levels of his target repetitive behavior (vocal stereotypy) were moderate and stable (*M* = 119, range = 90–140) in the silent condition, while levels in the noise condition were higher with slightly more variability (*M* = 155, range = 114–190). An overlap in levels across the two conditions was observed over sessions 5 and 6. However, a clear differentiation in the levels of target behavior was demonstrated between the two conditions across most of the sessions. NAP effect was 0.760 across the two conditions, indicating medium overlap. Marc's result suggested that the function of his target behavior was automatic negative reinforcement.

For Griffin, the levels of his target behavior (vocal stereotypy) ranged from moderate to high in both silent (*M* = 173, range = 124–229) and noise (*M* = 149, range = 84–202) conditions. The variability of data was large in both conditions, with no clear trend across 18 sessions. In addition, a substantial overlap in levels was observed between the two conditions. NAP effect was 0.667 across the two conditions, indicating a medium effect. As no visible differentiation in levels was observed and no predictive patterns emerged while levels remained relatively high in both conditions, Griffin's modified FA result suggested that the function of his target behavior was mixed automatic reinforcement.

For Aubrey, during the first six sessions, low levels of target behavior (vocal and motor stereotypy) were observed across both silent and noise conditions. In subsequent sessions, diminishing and near-zero levels of the target behavior were observed in both conditions. A change of room for logistical reasons beginning from session 10 did not influence her levels of target behavior in the subsequent study sessions. Up to session 14, the mean duration of target behavior in the silent condition was 16 s (range = 0–72) and 6 s in the noise condition (range = 0–44). When access to a preferred toy or item was introduced, observations across six sessions (session 15 to 21) showed no increase in the levels of target behavior in both conditions with a mean duration of 1 s (range = 0–4) in the silent condition and a mean duration of 3 s (range = 0–5) in the noise condition. Across all sessions of the modified FA, NAP effect was 0.355, indicating large overlap. Aubrey's modified FA result indicated a social reinforcement function.

Heart Rate Variability and Restricted and Repetitive Behaviors

A total of 83 modified FA sessions were implemented with five participants whose behavioral function was classified as automatic reinforcement (Cassie, Greta, Roger, Marc, and Griffin). Aubrey was excluded from the correlational analysis between HRV and RRB as her behavioral function was determined to be social reinforcement. Out of 83 modified FA sessions across the five participants, HRV data from 80 sessions (96%) were used to determine the correlation between the primary and secondary dependent variables, duration of RRB, and level of HRV. Three study sessions were excluded from the HRV analysis as HRV data were unavailable due to manual errors in the use of the digital wristband. A significant positive correlation was found between HRV and duration of repetitive behavior, $r\ (79) = .552$, $p < .001$. The scatterplot of the correlation analysis is displayed in Fig. 3, with different shapes of data points representing the three automatic reinforcement subtypes respectively. The mean HRV aggregated across participants was 0.0993 (SD = 0.010) in the silent condition and 0.0976 (SD = 0.013) in the noise condition. A Wilcoxon rank sum test (Wilcoxon, 1945) revealed no significant difference in HRV between conditions ($p = 0.81$).

Discussion

The current study aimed to identify potential subtypes of automatic reinforcement and determine if automatically maintained vocal or motor repetitive behavior in individuals with ASD is associated with autonomic arousal, as indexed by HRV.

Automatic Reinforcement Subtypes

Based on the results of the modified FA, five out of six participants (Cassie, Greta, Roger, Marc, and Griffin) were identified to have RRBs maintained by automatic reinforcement, while one participant (Aubrey) was identified to have RRBs maintained by social reinforcement. Among the five participants whose RRBs were determined to be automatically maintained, three participants (Cassie, Greta, and Roger) demonstrated behavior patterns that indicated a behavioral function of automatic positive reinforcement; one participant (Marc) demonstrated behavior patterns that indicated a behavior function of automatic negative reinforcement; one participant (Griffin) demonstrated behavior patterns that indicated a behavior function of mixed automatic reinforcement.

The deprived state in the silent condition of the modified FA created an establishing operation for the engagement of behavior maintained by access to stimulation. Conversely, when noncontingent auditory stimulation was provided in the noise condition, it provided an external source of stimulation that was not associated with social contingencies and created an abolishing operation for the engagement of behavior maintained by access to auditory stimulation

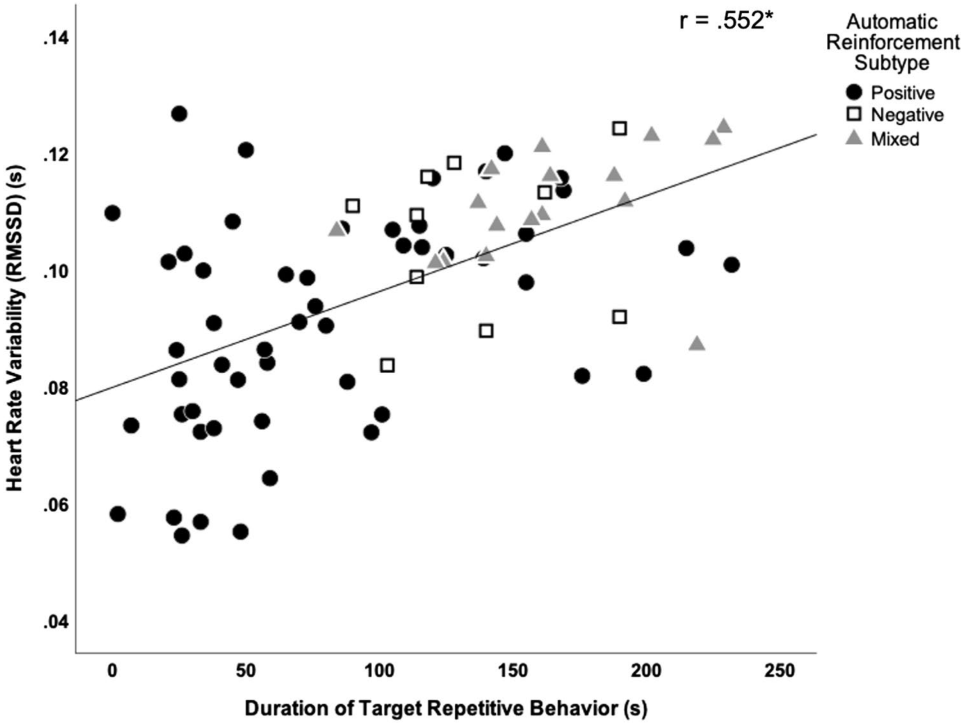

Fig. 3 Scatterplot of correlation of heart rate variability (RMSSD/s) and repetitive behavior across modified functional analysis sessions of five participants (Cassie, Greta, Roger, Marc, and Griffin); $r = .552$; $*p < .001$; data points were categorized based on automatic reinforcement subtypes including positive, negative, and mixed

(Laraway et al., 2003; Michael, 1993). Therefore, for the three participants (Cassie, Greta, and Roger) who engaged in more RRBs in the silent condition, it was deduced that their behavior produced automatic positive reinforcement. The unintended therapeutic change in RRB suggests that the continuous delivery of background noise provided a competing source of stimulation that resulted in a decrease of the behavior. This finding aligns with prior studies that demonstrated the effects of noncontingent auditory stimulus intervention (e.g., music, dialogue extracts from preferred TV shows or films) on RRBs maintained by automatic reinforcement (Cook & Rapp, 2020; Gibney et al., 2020; Lanovaz et al., 2014; Lanovaz & Sladeczek, 2012; Love et al., 2012; Rapp et al., 2013).

The high-stimulation environment presented in the noise condition likely created an establishing operation for the occurrence of behavior maintained by escape from stimulation, while the low-stimulation environment presented in the silent condition created an abolishing operation for the occurrence of behavior maintained by escape from stimulation. Therefore, for the participant (Marc) whose RRB was higher in the noise condition, the behavior was likely maintained by automatic negative reinforcement. This finding aligns with prior research that conceptualized automatic negative reinforcement as a potential functional subtype of the automatic reinforcement function (Rapp & Vollmer, 2005; Vollmer, 1994).

Griffin's overlapping levels of RRBs across both conditions indicated that he engaged in RRBs to (a) access stimulation that was not accessible in the silent environment and (b) escape from or reduce the stimulation he accessed in the noisy environment. Therefore, his RRBs were determined to be maintained by mixed automatic reinforcement. This finding aligns with some literature that suggests the possibility of a behavior producing both positive and negative reinforcement without the mediation of another person (e.g., scratching), which produces both sensory stimulation on the skin and the removal of physical discomfort (Cataldo & Harris, 1982; Iwata, Pace, et al., 1994). However, it should be noted that there is a possibility the experimental conditions (i.e., high and low stimulation) did not produce sufficient discrimination to differentially influence Griffin's level of repetitive behavior. As no further experimental phases were introduced to rule out this possibility, we acknowledge that our identification of mixed automatic reinforcement as a subtype in Griffin's case was made with less certainty than the other subtypes identified.

In the current study, when Aubrey's RRB was barely detectable in both conditions for several consecutive sessions, it was hypothesized that the FA setting might not have captured critical and relevant stimuli that were typically present in her natural settings, such as having free access to preferred items or toys. Hence, an additional phase of the modified FA with access to a preferred toy or item was introduced with the purpose of capturing a potentially relevant establishing operation for her RRB. Contrary to the hypothesis, Aubrey's RRB did not increase in either condition in the additional phase. It was thus concluded that Aubrey's screening assessment likely produced a false-positive result. However, as we did not include additional experimental phases to further verify that Aubrey's RRB was maintained by social reinforcement, this conclusion should be interpreted with caution.

Heart Rate Variability and Repetitive Behavior

A significant positive correlation was found between HRV and duration of RRBs across the modified FA sessions. Overall, when participants engaged in higher levels of RRBs, their HRV was higher. While this finding is preliminary and based on a small sample, it provides some support for the hypothesis that the external display of automatically reinforced RRB is associated with internal neurophysiological responses in children with ASD. Prior research has established that HRV is a relatively direct indicator of parasympathetic ANS activity (Friedman, 2007; Wass et al., 2015) and higher HRV tends to indicate more typical regulation of autonomic arousal, which influences an individual's behavior in response to the environment (Porges, 2007). Furthermore, a number of studies have demonstrated that individuals with ASD tend to have reduced HRV compared to neurotypical individuals (Guy et al., 2014; Lory et al., 2020; Neuhaus et al., 2014; Thapa et al., 2019, 2020). As such, our finding suggests that when individuals with ASD engage in more RRBs, it may help regulate autonomic arousal, as reflected by increased HRV. However, it should be noted that we did not investigate the relationship between socially maintained RRB and HRV. The scope of our experiment does not allow us to confirm an exclusive association between automatically maintained RRB and HRV responses. In addition, the use of RMSSD across a 5-min session as an index of HRV limits our ability to examine changes in HRV at specific time points either in response to environmental stimuli or as a consequence of RRB. Therefore, while the significant positive correlation found between RRB and HRV suggests an association between them, it is beyond the scope of this study to confirm if engaging in RRB resulted in HRV changes or if HRV changes led to the onset of RRB.

It may be of interest to note that the positive correlation between HRV and RRB found in this study may appear to misalign with some prior studies that found a negative correlation between HRV and more atypical reactivity to sensory stimulation in the environment (Lory et al., 2020) and severity of RRBs (Thapa et al., 2020) in individuals with ASD. However, findings should be interpreted in the context of the measures used in each study to draw more specific conclusions on the relationship between autonomic arousal and external behavior. In prior studies, measures of behavior involved indirect estimates of the frequency and severity of behavior, such as the Child Sensory Profile, Second Edition (Dunn, 2014). The external behavioral symptoms of ASD measured using these standardized assessments may or may not occur within the same window of time when HRV is measured. On the other hand, in the current study, RRBs were measured based on direct observations, while HRV was simultaneously measured. Therefore, the HRV changes across sessions within each participant in this study may be more representative of the participants' autonomic arousal across situations in their natural environment and more sensitive to the variation in levels of RRBs within an individual.

Implications for Research

This study offers preliminary evidence that a modified FA adapted from the protocol of the ignore condition in the analogue FA model (Iwata et al., 1994) can potentially be effective in delineating subtypes of automatic reinforcement, including (a) positive, (b) negative, and (c) mixed. The identification of automatic reinforcement subtypes aligns with the conceptualization of reinforcement as a contingency that may involve both the addition and removal of stimulus (Cooper et al., 2020) and literature that suggests the existence of both automatic positive and negative reinforcement (Rapp & Vollmer, 2005; Vollmer, 1994).

While some research has emerged to examine both the external display of challenging or interfering behavior and the internal physiological responses among individuals with developmental disabilities (Jennett et al., 2011; Lydon et al., 2013, 2015), no studies to date have examined the relationship between HRV and RRBs through simultaneous and direct measures of both variables utilizing an FA model of assessment. The current study piloted an integrated biobehavioral assessment approach for taking direct and simultaneous measures of RRB and HRV to better capture the immediate interaction between RRB and HRV. This is in contrast with the majority of prior research in this area that analyzed HRV against indirect measures of RRB. Future research in this area should leverage rapidly advancing technology and continue to expand the methods and contexts of examining the relationship between external and internal responses in individuals with ASD beyond traditional laboratory settings.

Furthermore, this study included young autistic children with relatively frequent and directly observable RRBs (e.g., out-of-context vocalizations, repeated motor movements) and low adaptive skills. This is in contrast with majority of the research that examined HRV in autistic individuals, as prior studies primarily recruited participants with ASD whose cognitive and adaptive abilities were comparable to neurotypical peers (Cheng et al., 2020). Considering the heterogeneity of cognitive and adaptive abilities among autistic individuals, with a majority proportion (over 50%) of the population receiving a diagnosis of mild to severe intellectual disability (Chiarotti & Venerosi, 2020), this study adds to the literature by including an underrepresented sample of children with ASD as participants in a study that measured their neurophysiological responses. Moreover, most of the prior studies collected HRV measures with participants in highly controlled laboratory settings. A novel feature of this study includes the examination of the potential effect and feasibility of a practitioner-implemented FA that included the use of a wearable device to collect both real-time RRBs and HRV data in the participants' natural settings. Study results and measures of procedural fidelity suggest that the assessment protocol was effective and feasible.

In addition, the current study points to the potential feasibility of coaching practitioners via a telehealth model (i.e., providing live coaching through video conferencing) to implement a screening assessment and a modified FA. A growing body of research has demonstrated that telehealth can be an effective service delivery model for supporting practitioners and caregivers to implement FAs with children with ASD in applied settings (Gerow et al., 2021; Machalicek et al., 2016; Wacker et al., 2013) and reduce geographical barriers and increase access to effective implementation of FAs and function-based interventions (Lindgren et al., 2016). This study contributes to the telehealth behavioral intervention literature by demonstrating the potential effectiveness of using telehealth to support practitioners in implementing a modified FA that involved the use of multiple technology devices (i.e., digital wristband, speaker, tablet, video camera). However, it should be noted that data recording and analyses were conducted by a researcher and the clinic staff had some experience in implementing ABA-based procedures.

Limitations and Future Directions

There are several limitations of this study that should be considered when interpreting the findings. First, auditory stimulation was the only variable that was systematically manipulated across the two conditions of the integrated assessment. The alternating presence and absence of white noise alone may not be the only variable that influences the occurrence of RRBs. To determine if automatically maintained RRBs may be sensitive to a wider array of environmental stimulation, future research should consider incorporating other types of stimulation (e.g., visual, tactile) while controlling for the delivery of social stimuli and contingencies.

Second, an absence of baseline or resting condition prior to each study session did not allow for the examination of whether HRV levels increased or decreased differently from each participant's initial state to the silent and noise condition, respectively. To determine HRV reactivity in the context of different levels of environmental stimulation, future research should consider collecting baseline HRV data immediately prior to each study condition where the independent variable is manipulated.

Third, motion was not accounted for as a variable in our analyses. The researcher monitored all study sessions via a video conferencing tool, which created a barrier to the verification of whether the wristband fit tightly on each participant's wrist at the beginning of each session. Further, the design of the modified FA required the clinic staff to withhold social attention from the participants, and participants were free to move about within a vacant study room without any requirement to stay in a designated area. Thus, behaviors that might have produced artifact in the HRV data (e.g., rapid clapping or waving of hands, knocking hands on objects) or increased changes in heart rate (e.g., physical exertion from motor stereotypy or walking) were not stopped. These factors might have contributed to motion-related artifacts in HRV. While we believe it is a strength of this study to pilot a biobehavioral assessment protocol in an applied setting to simulate a more natural environment rather than laboratory settings where HRV data have conventionally been collected, we recognize the importance of further exploration of appropriate technology and assessment protocol to collect physiological data of children with ASD who engage in unrestricted movements during data collection.

Fourth, this study included a small sample of participants with a primary focus of examining within-participant changes in RRBs and HRV. While the study provides some preliminary evidence for (a) the utilization of a modified FA to delineate automatic reinforcement subtypes and (b) exploring the underlying neurophysiological mechanisms that interact with the occurrence of RRBs in children with ASD, replication of study findings with a wider population is necessary to make more definite conclusions.

Fifth, the ASD diagnoses of participants included in this study were confirmed through a review of their clinical records, which did not contain standardized indicators of ASD severity or adaptive functioning. Future research interested in examining the relationship between RRB and HRV in children with ASD should include assessments to corroborate ASD diagnosis and provide clear indicators of ASD severity and adaptive functioning.

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Author Contribution CL conceived of and designed the study. MR, BK, RAM, and BAM participated in the design of the study. CL implemented the study. CL, SK, AMB, ES, and HC acquired the data. CL analyzed the data and drafted the manuscript. MR and BK helped revise the manuscript.

Declarations

Ethics Approval This study was approved by the Institutional Review Board of Purdue University (Protocol number IRB-2019-710).

Competing Interests The authors declare no competing interests.

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