Preventive Medicine Reports 24 (2021) 101638

Contents lists available at ScienceDirect

Preventive Medicine Reports

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

Relationship between heart rate variability and body mass index: A cross-sectional study of preschool children

Kathryn E. Speer[a,b,*], Julian Koenig[i], Rohan M. Telford[b], Lisa S. Olive[e,f], Jocelyn K. Mara[a,b], Stuart Semple[a,b], Nenad Naumovski[c,g,h], Richard D. Telford[b], Andrew J. McKune[a,b,d]

[a] Faculty of Health, Discipline of Sport and Exercise Science/University of Canberra, Canberra, ACT, Australia
[b] Research Institute for Sport and Exercise/University of Canberra, Canberra, ACT, Australia
[c] Faculty of Health, University of Canberra, Discipline of Nutrition and Dietetics/University of Canberra, Canberra, ACT, Australia
[d] Discipline of Biokinetics, Exercise and Leisure Sciences, School of Health Sciences/ University of KwaZulu-Natal, Durban, KwaZulu-Natal, South Africa
[e] Centre for Social and Early Emotional Development, Faculty of Health, Deakin University, Geelong, Victoria, Australia
[f] IMPACT, The Institute for Mental and Physical Health and Clinical Translation, Faculty of Health, Deakin University, Geelong, Victoria, Australia
[g] Functional Foods and Nutrition Research (FFNR) Laboratory, University of Canberra, Bruce, ACT, Australia
[h] Department of Nutrition and Dietetics, Harokopio University, Athens 17671, Greece
[i] University of Cologne, Faculty of Medicine and University Hospital Cologne, Department of Child and Adolescent Psychiatry, Psychosomatics and Psychotherapy, Cologne, Germany

ARTICLE INFO

Keywords:
'Heart rate variability' or 'HRV'
'Vagal activity'
'Body mass index' or 'BMI'
Children
'Physical activity'

ABSTRACT

Reduced heart rate variability (HRV) is associated with overweight and obesity in adults. However, little is known about this relationship in early childhood. We investigated the relationship between resting vagally-mediated HRV and body mass index (BMI) in Australian preschool children. Children were recruited from 13 non-government early learning centres located in Queensland and New South Wales, Australia. From this population-based sample, data from 146 healthy children (58 females) between 3 and 5 years of age (mean age 4.35 ± 0.44 years) were analysed. BMI was calculated from child body weight and height. Physical activity was recorded using an Actigraph wGT3x accelerometer worn at the waist of participants over 3 consecutive days. A Polar *H*10 chest strap measured seated, resting RR intervals for the calculation of HRV with the root mean square of successive differences (RMSSD) reflecting vagally-mediated activity. The relationship between HRV and BMI was analysed using a linear mixed model adjusted for age, sex and physical activity. Analysis revealed that RMSSD (ln) demonstrated a significant inverse relationship with BMI ($\beta = -0.06$; 95% CI = -0.12 – −0.01; $p = 0.032$), and the model accounted for 23% of the variance in RMSSD (ln). Notably, a one unit increase in BMI resulted in a reduction in RMSDD (ln) of 0.06. This investigation demonstrated evidence for a significant inverse linear relationship between vagally-mediated HRV and BMI in 3 – 5-year-old Australian children, similar to that of adults. Furthermore, this relationship was independent of age, sex and physical activity levels. Results may indicate that the cardiometabolic health of preschool children is, in part, influenced by the relationship between vagally-mediated HRV and weight status.

1. Introduction

Obesity and its associated comorbidities, including impaired glucose tolerance, insulin resistance, dyslipidaemia, elevated blood pressure and sleep apnoea are prevalent in children (Campbell, 2016; Frey et al., 2015). Underlying the physical burden of obesity includes disruptions to the autonomic nervous system (Triggiani et al., 2017). During acute physical or psychological stress, Sympathetic contribution of total autonomic activity increases with a reduction in parasympathetic involvement until the stress has dissipated (Taralov et al., 2015). This phenomenon encourages physiological adaptations which may improve physical and cognitive health/resilience (Parry et al., 2018). However, ongoing stress maintains elevated sympathetic activity, promotes systemic inflammation and cytokine activation which may result in insulin resistance and increased lipid production in the liver. Eventually, the culmination of these physiological disturbances may manifest as

---

* Corresponding author at: Faculty of Health, Discipline of Sport and Exercise Science/University of Canberra, Canberra, ACT, Australia.
E-mail address: katie.speer@canberra.edu.au (K.E. Speer).

https://doi.org/10.1016/j.pmedr.2021.101638
Received 24 March 2021; Received in revised form 2 October 2021; Accepted 13 November 2021

cardiovascular or metabolic disease related complications (Triggiani et al., 2017; Saito et al., 2017).

Heart rate variability (HRV) is a non-invasive marker of autonomic cardiac vagal regulation and is linked with many pathological conditions (Laborde et al., 2018; Laborde et al., 2017). The root mean square of successive differences (RMSSD), a short-term time-domain HRV parameter, specifically reflects parasympathetic/vagal activity, with higher RMSSD at rest typically representing "*healthy*" vagally-mediated autonomic activity (Laborde et al., 2018; de Geus et al., 2019). Reduced resting state HRV, represented by lower RMSSD values, has been demonstrated in children with obesity-related health complications and is an established risk factor for insulin resistance, cardiometabolic diseases and potentially early mortality (Leppänen et al., 2020; Saito et al., 2017; Shaffer and Ginsberg, 2017).

Although mostly studied in adults, the inverse relationship between HRV and overweight and obesity [as determined by body mass index (BMI)] is such that decreased overall HRV (i.e. decreased parasympathetic activity) is associated with a higher BMI (Birch et al., 2012; Koenig et al., 2014). Physical activity has also demonstrated an inverse relationship with BMI, with lower physical activity levels associated with increased BMI and cardiometabolic disease risk (Iellamo and Volterrani, 2013). Notably, previous findings indicate an interplay between physical activity, HRV, and BMI (Saito et al., 2015; Soares-Miranda et al., 2012; Soares-Miranda et al., 2014; Speer et al., 2019). One such study in children 6 – 12 years old observed significantly higher HRV in the '*lean-active*' group compared with '*lean-inactive*'; ' *obese-active*' and '*obese-inactive*' groups (Nagai and Moritani, 2004). Furthermore, the '*obese-inactive*' participants exhibited the lowest HRV relative to all other groups, which may exacerbate cardiometabolic disease risk (Nagai and Moritani, 2004).

Research into the relationship between HRV and BMI in preschool children (<6 years old) is limited providing further complexities in the establishment of obesity/overweight classifications in this population sample. Considering the dysregulated autonomic underpinnings of obesity, HRV can potentially act as a screening tool to identify children at risk of cardiometabolic related health complications. Therefore, the aim of the present study was to evaluate the relationship between resting vagally-mediated HRV and BMI in Australian children (Speer et al., 2020).

2. Methods

The study was approved by the University of Canberra Human Research Ethics Committee, Research Ethics and Integrity Review Board (UCHREC: 2019–1853). This cross-sectional study investigated baseline data from a subgroup of the Active Early Learning study, which was a 6-month randomised controlled, longitudinal trial to investigate the effects of a physical literacy professional development and curriculum support program for early learning centre educators (Telford et al., 2021). A total of 321 children (n = 135 females, n = 186 males, mean age = 4.29 ± 0.43 years) from 16 non-government early learning centres in Queensland and New South Wales (Australia) were recruited as part of the Active Early Learning intervention trial (Australian New Zealand Clinical Trials registry number: ACTRN12619000638134).

2.1. Sample population

One hundred and fifty eligible children were recruited as a population-based sample from 11/16 of the early learning centres. Children were eligible if they were enrolled in the preschool class of the participating early learning centres and were at least 3 years old at the time of evaluation. Participants were excluded if they were sick on the day of testing or within the week leading up to testing. Parents/guardians of eligible children were provided with a participant information pack outlining the study objectives and measurement procedures before providing consent. Prior to baseline measurements, the parents/guardians of participants provided their written informed consent and participants communicated their assent. Four children were excluded due to incomplete datasets. Statistical analyses were performed on n = 146 children (45% of total Active Early Learning study population).

2.2. Assessment of physical activity

Physical activity data were collected over three consecutive days during early learning centre operating hours. The Actigraph wGT3x accelerometer waist belt (Pensicola, FL, USA) was secured around each participant's waist for collection of moderate-vigorous physical activity (MVPA) data. Delegated educators, who received training for fitting the accelerometers, secured the waist belt as each participant arrived to the early learning centre and removed it just prior to participant departure from the centre. Activity cut points (counts/60 s) were set for MVPA (above 1680) and data were included in the analysis provided there were at least 3 h of valid wear time with non-wear periods classified as ≥ 20 min in accordance with a previous study on physical activity in preschool children (Okely et al., 2020). A full detail of the techniques and criteria for measuring physical activity in this population has been previously described (Telford et al., 2021).

2.3. Assessment of HRV and BMI

All measurements were conducted in the morning (between 8:00am and 12:00 pm) at each early learning centre, except for one that was visited in the afternoon. An electronic scale and stadiometer were used to measure body weight and height with standardised techniques (Telford et al., 2021). BMI was subsequently calculated as body weight (kg)/height squared (m^2). Given that food ingestion appears to impact autonomic activity, it was ensured that all participants had not eaten within an hour of data collection (Tentolouris et al., 2003).

To determine resting autonomic activity, each participant was fitted with a Polar *H*10 Heart Rate Sensor chest strap, which detects and processes the heart's electrical signals. Using Bluetooth 4.0, the chest strap wirelessly connected to the EliteHRV© app on an iPhone. Upon signal recognition, the "*open reading*" option on the EliteHRV© app was selected. Once heart rate stabilised (approximately two minutes), the investigator pressed "*start*" on the app to commence HRV recordings. Through signal processing, the heart's electrical signals were converted into raw interbeat (RR) intervals, which were exported (in milliseconds) as a text file and uploaded to Kubios heart rate variability software (version 3.1.0, Biosignal Analysis and Medical Imaging Group, Department of Physics, University of Kuopio, Kuopio, Finland) for data correction and analysis. Prior to analysis, the data were manually reviewed and corrected for ectopic beats using methods described elsewhere (Speer et al., 2020; Nunan et al., 2009). Following manual correction of the raw RR intervals, statistical analyses were conducted on RMSSD derived from the Kubios software program.

The Polar *H*10 chest strap has demonstrated comparable validity for HRV measurements to that of electrocardiographic-derived recordings (Gilgen-Ammann et al., 2019). Furthermore, valid and reliable HRV measurements via the Polar *H*10 chest strap have been established in this age group (i.e. 3 – 5 years of age) (Speer et al., 2020). As previously described, Velcro was sewn onto the reverse side of the Polar *H*10 chest strap prior to data collection for adjustability between participants, ensuring an accurate and personalised fit around each child (Speer et al., 2020). The HRV of each participant was measured in a seated, resting state for 3.5 min (including a 30 s stabilisation period) in a one-on-one setting with the investigator using the methods and protocol outlined in earlier research (Speer et al., 2020; Krejčí et al., 2018).

The parameter, RMSSD, was selected to specifically represent vagally-mediated HRV using the guidelines recommended by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology ([29]). Additionally, previous findings have indicated that RMSSD can be reliably measured in this age group and is less affected by respiration (Speer et al., 2020; Thomas et al., 2019).

2.4. Statistical analysis

Microsoft Excel 2016 and the statistical software package R (version 4.0.3) were used to analyse the relationship between RMSSD and BMI (Team RC. R, 2020). Participant demographics are presented as mean ± SD. Due to its non-normally distributed nature, the natural logarithm (Ln) of RMSSD was calculated. Linear mixed modelling analyses were performed using *lme4* R package RMSSD (ln) was assumed as the dependent variable with BMI, age, sex and MVPA were set as the fixed factors, and early learning centre as a random factor. As sex differences in HRV have been observed in children, an interaction term for BMI and sex was also included in the model to determine sex-specific associations (Koenig et al., 2017; Bates et al., 2014). The assumption of normality was confirmed using a histogram and Q-Q plot of the residuals, and the assumption of homoscedasticity upon visual inspection of a plot of the fitted values against the residuals. Significant associations were considered at $p < 0.05$.

3. Results

A summary of participant characteristics by group and sex are presented in Table 1. From the original sample, n = 146 healthy children (n = 58 females, n = 88 males) between the ages of 3 and 5 years old (mean age = 4.35 ± 0.44 years) participated in this study.

Linear mixed model analyses revealed an inverse relationship ($p =$ 0.025) between RMSSD (ln) and BMI independent of age, sex and MVPA levels (Table 2 and Fig. 1). Specifically, a one unit increase in BMI resulted in a reduction in RMSSD (ln) by 0.06 with 23% of the variance in RMSSD (ln) explained by the model.

4. Discussion

Previous research has provided evidence for a linear, inverse relationship between vagally-mediated autonomic activity and BMI in adults (Koenig et al., 2014; Molfino et al., 2009). The current study sought to investigate the relationship between RMSSD, as a marker of cardiac vagally-mediated autonomic activity, and BMI in young children. To the best of our knowledge, this is the first study to replicate an inverse linear relationship between RMSSD and BMI, independent of age, sex and physical activity, in a population-based sample of children aged 3 – 5 years old. Consequentially, it was also found that a one unit increase in BMI resulted in a decrease in RMSSD (ln) by 0.06.

Table 1
Participant characteristics (mean ± SD).

	Group(n = 146)	Boys(n = 88)	Girls(n = 58)	Significance (p-value)
Age (years)	4.34 ± 0.44	4.37 ± 0.47	4.34 ± 0.41	0.704
Height (cm)	105.03 ± 5.33	105.06 ± 5.31	104.99 ± 5.32	0.422
Weight (kg)	17.96 ± 2.72	17.95 ± 2.73	17.96 ± 2.73	0.586
BMI (kg/m^2)	16.95 ± 1.85	16.94 ± 1.85	16.95 ± 1.86	0.773
MVPA (min/hr)	4.20 ± 2.40	4.80 ± 2.40	3.60 ± 2.40	0.031*
Average accelerometer wear time (hrs/day)	7.01 ± 1.32	6.88 ± 1.27	7.21 ± 1.39	0.177
Mean RR (ms)	575.44 ± 52.72	577.92 ± 52.71	571.67 ± 52.97	0.485
Resting HR (bpm)	105.11 ± 9.34	105.24 ± 9.33	105.26 ± 9.20	0.470
RMSSD (ln)	4.65 ± 0.09	4.65 ± 0.09	4.66 ± 0.09	0.512

BMI: body mass index; MVPA: moderate-vigorous physical activity; HR: heart rate; RMSSD: root mean square of successive differences.
*Denotes statistical significance with $p < 0.05$.

Table 2
Linear mixed model analyses of covariates on HRV.

	RMSSD (ln)		
Fixed Effects	*Estimates*	*95% CI*	*p*
BMI	−0.06	−0.12 – −0.01	0.025*
Age	0.10	−0.11 – 0.30	0.356
Sex (girl)	−0.12	−1.76 – 1.52	0.231
MVPA	−1.23	−3.64 – 1.24	0.328
BMI × Sex	< −0.01	−0.10 – 0.10	0.999
Random Effects*			
Between-Centre Variance	0.07		
Residual Variance	0.28		
N: Centres	11		
N: Participants	146		
N: Observations	142		

Note: HRV, heart rate variability; BMI, body mass index; MVPA, moderate-vigorous physical activity; RMSSD, root mean square of successive differences; ln, natural logarhm; CI, confidence intervals
*$p < 0.05$
**Random effects are shown as estimates

The inverse relationship between RMSSD and BMI has also been observed in older children ($\geq$6 years) (Birch et al., 2012; Santos-Magalhaes et al., 2015; Taşçılar et al., 2011; Vanderlei et al., 2010). Furthermore, lower vagally-mediated HRV parameters [e.g. RMSSD, high frequency (HF) band] were particularly evident amongst children (aged 6 to 15 years) with overweight ($\geq 85^{th}$ but $<$ 95th percentile) and obese ($\geq 95^{th}$ percentile) BMI classifications (Birch et al., 2012; Santos-Magalhaes et al., 2015; Taşçılar et al., 2011; Vanderlei et al., 2010). It is possible that, compared with children fitting the “*normal*” BMI categories, children with “*overweight*” and “*obese*” range of BMI values endure adverse metabolic stress, characterised by parasympathetic withdrawal and sympathetic hyperactivity (Nagai and Moritani, 2004; Santos-Magalhaes et al., 2015; Taşçılar et al., 2011).

A unique finding in the current study is that HRV confounders such as age, sex and physical activity levels did not influence the relationship between HRV and BMI in this sample of 3 – 5-year-old children. Regarding age as a confounder, Birch et al. (Birch et al., 2012) and Herzig et al. (Herzig et al., 2017) both indicated that age significantly influenced child vagally-mediated HRV (Birch et al., 2012; Herzig et al., 2017). Additionally, Silvetti and colleagues (2001) demonstrated that HRV is partially related to age and sex in healthy children (Silvetti et al., 2001). Importantly, the latter study included participants from 1 to 20 years of age and did not demonstrate significant differences between girls and boys (1 and 5 years old) for RMSSD (Silvetti et al., 2001).

Regarding physical activity levels, MVPA may not stimulate enough cardiovascular stress in children this young and, perhaps, more vigorous levels of physical activity may lead to autonomic adaptations (Farah et al., 2014). The physical activity results in the current study were similar to an investigation that recruited older children (aged 6 – 10 years), which demonstrated a relationship between low vagally-mediated HRV and high BMI despite participant physical activity levels (Santos-Magalhaes et al., 2015). In contrast, Nagai and Moritani (Nagai and Moritani, 2004) demonstrated that children who were obese as well as inactive (defined as participating in $\leq$ 60-min aerobic exercise/sports $\leq$ 3 times per week) exhibited significantly lower total HRV than age-, height- and sex-matched active obese children (Nagai and Moritani, 2004). Similarly, amongst overweight and obese children, lower physical activity levels were significantly associated with lower HRV (Chen et al., 2012).

Importantly, it is still relatively unknown whether pre-existing physical (e.g. BMI) or environmental (e.g. physical activity, diet) risk factors induce autonomic dysregulation or if the opposite is true (i.e. altered cardiac vagal tone leads to physical and/or behavioural

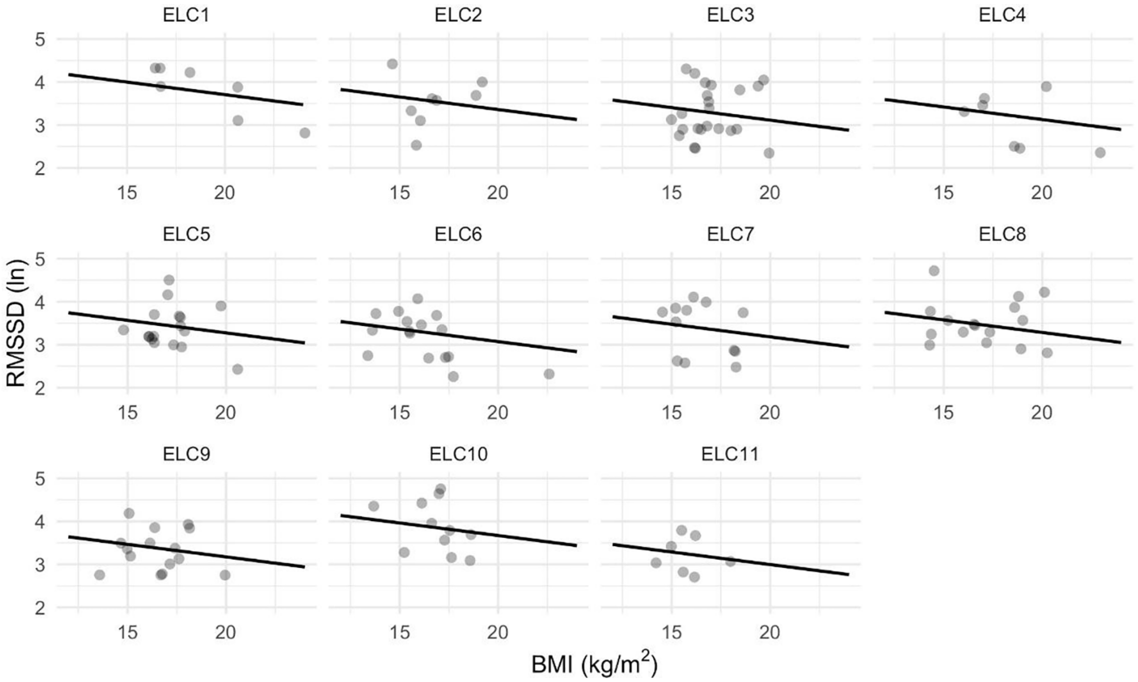

Fig. 1. The relationship between BMI and RMSSD (ln) with random intercept model fits for each early learning centre. Note: The points represent the raw data for BMI and RMSSD (ln) and the lines represent the random intercept model fits for each early learning centre, with age, sex and MVPA held fixed. A random slope for each early learning centre was found to be non-significant ($p = 0.544$) and therefore the slopes remain fixed for each early learning centre.

changes). Indeed, childhood obesity has been acknowledged as a risk factor for cardiometabolic complications including high blood pressure, insulin resistance, abnormal lipid profiles and low HRV (Plaza-Florido et al., 2019). However, given that the vagus nerve innervates the gastrointestinal system, vagal activity may determine hunger as well as its associated behaviours and potentially body composition (Feldman and Richardson, 1986; Peschel et al., 2016; Lambert et al., 2011). More specifically, autonomic dysregulation may modify ghrelin secretion, driving feelings of hunger/satiety, implicating BMI and cardiometabolic disease risk in both underweight and overweight individuals (Peschel et al., 2016; Huda et al., 2010; Monteleone et al., 2008). Considering this uncertainty, characterisation of the complexities and nature of the interaction between somatic/environmental factors and autonomic dysregulation may facilitate the development of a more targeted approach which may be used by caregivers, medical/health professionals, policy makers, etc to improve the cardiometabolic health of children.

The investigators acknowledge several strengths and limitations for the current study. Regarding strengths, the study sample consisted of a relatively large population-based sample of 3 – 5-year-old children recruited from various early learning centres in Queensland, Australia. This study also controlled for physical activity levels and used the PolarH10 Heart Rate Sensor to record HRV, which has previously been identified as a reliable and valid device to measure HRV in this age group (Speer et al., 2020). However, the cross-sectional nature of this study prohibits any causal relationships that may be determined from the results. Furthermore, this study compares HRV parameters across a range of BMIs in an early childhood population. Whilst BMI can be a reliable indicator of weight status in normal weighted populations, it is not a measure of body fat and does not account for sex and age, which are important factors to consider for early childhood growth patterns (Kwieciński et al., 2018; Reginato et al., 2020). Also, confounding factors such as environment (indoor vs outdoor measurements), sleep, diet, physical activity over the entire day or outside of the early learning centre, cardiorespiratory fitness, socioeconomic status, race/ethnicity and behaviour were not controlled for [50]. Moreover, there was an uneven number of girls relative to boys in this study (females = 58; boys = 88), with a larger proportion of non-normal weighted girls than boys. Lastly, although 23% of the variance in RMSSD (ln) was explained by the model, there is still 77% of the variance in RMSSD (ln) left unexplained. Thus, the results should be interpreted with caution.

This study builds upon previous research supporting an association between autonomic activity and BMI by providing evidence for an inverse linear relationship between cardiac vagal HRV and BMI in children aged 3 – 5 years old. Furthermore, evidence indicated that age, sex and physical activity did not influence this relationship, which may suggest that the cardiometabolic health of preschool children is partially determined by a link between autonomic activity and body composition. Such knowledge could provoke further research into the development of HRV as a potential screening tool or classification method for young children at risk of health issues related to body composition, glycaemic control and/or cardiac autonomic neuropathy.

CRediT authorship contribution statement

Kathryn E. Speer: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Julian Koenig:** Formal analysis, Writing – review & editing. **Rohan M. Telford:** Conceptualization, Formal analysis, Investigation, Data curation, Visualization, Project administration, Writing – review & editing. **Lisa S. Olive:** Conceptualization, Data curation, Project administration, Writing – review & editing. **Jocelyn K. Mara:** Formal analysis, Visualization, Writing – review & editing. **Stuart Semple:** Supervision, Writing – review & editing. **Nenad Naumovski:** Supervision, Writing – review & editing. **Richard D. Telford:** Conceptualization, Investigation, Data curation, Visualization, Project administration, Writing – review & editing. **Andrew J. McKune:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Visualization, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

None.

Funding

The lead author, KES, is a recipient of the Research Training Program scholarship from the Department of Education, Australia.

References

Campbell, M.K., 2016. Biological, environmental, and social influences on childhood obesity. Pediatr Res. 79 (1-2), 205–211.

Frey, U., Latzin, P., Usemann, J., Maccora, J., Zumsteg, U., Kriemler, S., 2015. Asthma and obesity in children: current evidence and potential systems biology approaches. Allergy. 70 (1), 26–40.

Leppänen, M.H., Haapala, E.A., Veijalainen, A., Seppälä, S., Oliveira, R.S., Lintu, N., Laitinen, T., Tarvainen, M.P., Lakka, T.A., 2020. Associations of cardiometabolic risk factors with heart rate variability in 6- to 8-year-old children: The PANIC Study. Pediatr Diabetes. 21 (2), 251–258.

Triggiani, A.I., Valenzano, A., Ciliberti, M.A.P., Moscatelli, F., Villani, S., Monda, M., Messina, G., Federici, A., Babiloni, C., Cibelli, G., 2017. Heart rate variability is reduced in underweight and overweight healthy adult women. Clin Physiol Funct Imaging. 37 (2), 162–167.

Taralov, Z.Z., Terziyski, K.V., Kostianev, S.S., 2015. Heart Rate Variability as a Method for Assessment of the Autonomic Nervous System and the Adaptations to Different Physiological and Pathological Conditions. Folia medica. 57 (3–4), 173–180.

Parry, D.A., Oeppen, R.S., Amin, M.S.A., Brennan, P.A., 2018. Could exercise improve mental health and cognitive skills for surgeons and other healthcare professionals? Br J Oral Maxillofac Surg. 56 (5), 367–370.

Saito, I., Maruyama, K., Eguchi, E., Kato, T., Kawamura, R., Takata, Y., Onuma, H., Osawa, H., Tanigawa, T., 2017. Low Heart Rate Variability and Sympathetic Dominance Modifies the Association Between Insulin Resistance and Metabolic Syndrome - The Toon Health Study. Circ J. 81 (10), 1447–1453.

Laborde, S., Mosley, E., Mertgen, A., 2018. Vagal Tank Theory: The Three Rs of Cardiac Vagal Control Functioning - Resting, Reactivity, and Recovery. Front Neurosci. 12, 458.

Laborde, S., Mosley, E., Thayer, J.F., 2017. Heart Rate Variability and Cardiac Vagal Tone in Psychophysiological Research – Recommendations for Experiment Planning. Data Analysis, and Data Reporting. Front Psychol. 8 (213).

de Geus, E.J.C., Gianaros, P.J., Brindle, R.C., Jennings, J.R., Berntson, G.G., 2019. Should heart rate variability be “corrected” for heart rate? Biological, quantitative, and interpretive considerations. Psychophysiology. 56 (2), e13287. https://doi.org/10.1111/psyp.2019.56.issue-210.1111/psyp.13287.

Shaffer, F., Ginsberg, J.P., 2017. An Overview of Heart Rate Variability Metrics and Norms. Front Public Health. 5, 258.

Birch, S.L., Duncan, M.J., Franklin, C., 2012. Overweight and reduced heart rate variability in British children: An exploratory study. Prev Med. 55 (5), 430–432.

Koenig, J., Jarczok, M.N., Warth, M., Ellis, R.J., Bach, C., Hillecke, T.K., Thayer, J.F., 2014. Body mass index is related to autonomic nervous system activity as measured by heart rate variability–a replication using short term measurements. J Nutr Health Aging. 18 (3), 300–302.

Iellamo, F., Volterrani, M., 2013. Childhood obesity, autonomic cardiovascular regulation and regular physical activity. Heart. 99 (6), 359–360.

Saito, I., Hitsumoto, S., Maruyama, K., Nishida, W., Eguchi, E., Kato, T., Kawamura, R., Takata, Y., Onuma, H., Osawa, H., Tanigawa, T., 2015. Heart Rate Variability, Insulin Resistance, and Insulin Sensitivity in Japanese Adults: The Toon Health Study. J Epidemiol. 25 (9), 583–591.

Soares-Miranda, L., Sandercock, G., Vale, S., Santos, R., Abreu, S., Moreira, C., Mota, J., 2012. Metabolic syndrome, physical activity and cardiac autonomic function. Diabetes Metab Res Rev. 28 (4), 363–369.

Soares-Miranda, L., Sattelmair, J., Chaves, P., Duncan, G.E., Siscovick, D.S., Stein, P.K., Mozaffarian, D., 2014. Physical activity and heart rate variability in older adults: the Cardiovascular Health Study. Circulation. 129 (21), 2100–2110.

Speer KE, Naumovski N, Semple S, McKune AJ. Lifestyle Modification for Enhancing Autonomic Cardiac Regulation in Children: The Role of Exercise. Children (Basel, Switzerland). 2019;6(11).

Nagai, N., Moritani, T., 2004. Effect of physical activity on autonomic nervous system function in lean and obese children. Int J Obes Relat Metab Disord. 28 (1), 27–33.

Speer, K.E., Semple, S., Naumovski, N., McKune, A.J., 2020. Measuring Heart Rate Variability Using Commercially Available Devices in Healthy Children: A Validity and Reliability Study. Eur J Investig Health Psychol Educ. 10 (1), 390–404.

Telford, R.M., Olive, L.S., Telford, R.D., 2021. A peer coach intervention in childcare centres enhances early childhood physical activity: The Active Early Learning (AEL) cluster randomised controlled trial. Int J Behav Nutr Phys Act. 18 (1), 37.

Okely, A.D., Stanley, R.M., Jones, R.A., Cliff, D.P., Trost, S.G., Berthelsen, D., Salmon, J. o., Batterham, M., Eckermann, S., Reilly, J.J., Brown, N., Mickle, K.J., Howard, S.J., Hinkley, T., Janssen, X., Chandler, P., Cross, P., Gowers, F., 2020. ’Jump start’ childcare-based intervention to promote physical activity in pre-schoolers: six-month findings from a cluster randomised trial. Int J Behav Nutr Phys Act. 17 (1) https://doi.org/10.1186/s12966-020-0910-6.

Tentolouris, N., Tsigos, C., Perea, D., Koukou, E., Kyriaki, D., Kitsou, E., Daskas, S., Daifotis, Z., Makrilakis, K., Raptis, S.A., Katsilambros, N., 2003. Differential effects of high-fat and high-carbohydrate isoenergetic meals on cardiac autonomic nervous system activity in lean and obese women. Metabolism. 52 (11), 1426–1432.

Nunan, D., Donovan, G., Jakovljevic, D.G., Hodges, L.D., Sandercock, G.R., Brodie, D.A., 2009. Validity and reliability of short-term heart-rate variability from the Polar S810. Med Sci Sport Exerc. 41 (1), 243–250.

Gilgen-Ammann, R., Schweizer, T., Wyss, T., 2019. RR interval signal quality of a heart rate monitor and an ECG Holter at rest and during exercise. Eur J Appl Physiol. 119 (7), 1525–1532.

Krejčí J, Botek M, McKune AJ. Stabilization period before capturing an ultra-short vagal index can be shortened to 60 s in endurance athletes and to 90 s in university students. PLOS ONE. 2018;13(10):e0205115.

[29] Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation. 1996;93(5):1043-65.

Thomas, B., Claassen, N., Becker, P., Viljoen, M., 2019. Validity of Commonly Used Heart Rate Variability Markers of Autonomic Nervous System Function. Neuropsychobiology. 78 (1), 14–26.

Team RC. R, 2020. A language and environment for statistical computing. In: Computing RFfS, editor. Vienna, Austria European Environment Agency.

Koenig, J., Rash, J.A., Campbell, T.S., Thayer, J.F., Kaess, M., 2017. A Meta-Analysis on Sex Differences in Resting-State Vagal Activity in Children and Adolescents. Front Physiol. 8, 582.

Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:14065823. 2014.

Molfino, A., Fiorentini, A., Tubani, L., Martuscelli, M., Fanelli, F.R., Laviano, A., 2009. Body mass index is related to autonomic nervous system activity as measured by heart rate variability. Eur J Clin Nutr. 63 (10), 1263–1265.

Santos-Magalhaes, A.F., Aires, L., Martins, C., Silva, G., Teixeira, A.M., Mota, J., Rama, L., 2015. Heart rate variability, adiposity, and physical activity in prepubescent children. Clin Autonom Res. 25 (3), 169–178.

Taşçılar, M.E., Yokuşoğlu, M., Boyraz, M., Baysan, O., Köz, C., Dündaröz, R., 2011. Cardiac autonomic functions in obese children. J Clin Res Pediatr Endocrinol. 3 (2), 60–64.

Vanderlei, L.C., Pastre, C.M., Freitas Júnior, I.F., Godoy, M.F., 2010. Analysis of cardiac autonomic modulation in obese and eutrophic children. Clinics (Sao Paulo, Brazil). 65 (8), 789–792.

Herzig, D., Eser, P., Radtke, T., Wenger, A., Rusterholz, T., Wilhelm, M., Achermann, P., Arhab, A., Jenni, O.G., Kakebeeke, T.H., Leeger-Aschmann, C.S., Messerli-Bürgy, N., Meyer, A.H., Munsch, S., Puder, J.J., Schmutz, E.A., Stülb, K., Zysset, A.E., Kriemler, S., 2017. Relation of Heart Rate and its Variability during Sleep with Age, Physical Activity, and Body Composition in Young Children. Front Physiol. 8 https://doi.org/10.3389/fphys.2017.00109.

Silvetti, M.S., Drago, F., Ragonese, P., 2001. Heart rate variability in healthy children and adolescents is partially related to age and gender. Int J Cardiol. 81 (2-3), 169–174.

Farah, B.Q., Ritti-Dias, R.M., Balagopal, P.B., Hill, J.O., Prado, W.L., 2014. Does exercise intensity affect blood pressure and heart rate in obese adolescents? A 6-month multidisciplinary randomized intervention study. Pediatr Obes. 9 (2), 111–120.

Chen, S.-R., Chiu, H.-W., Lee, Y.-J., Sheen, T.-C., Jeng, C., 2012. Impact of pubertal development and physical activity on heart rate variability in overweight and obese children in Taiwan. J Sch Nurs. 28 (4), 284–290.

Plaza-Florido, A., Migueles, J.H., Mora-Gonzalez, J., Molina-Garcia, P., Rodriguez-Ayllon, M., Cadenas-Sanchez, C., Esteban-Cornejo, I., Navarrete, S., Maria Lozano, R., Michels, N., Sacha, J., Ortega, F.B., 2019. The Role of Heart Rate on the Associations Between Body Composition and Heart Rate Variability in Children With Overweight/Obesity: The ActiveBrains Project. Front Physiol. 10 https://doi.org/10.3389/fphys.2019.0089510.3389/fphys.2019.00895.s001.

Feldman, M., Richardson, C.T., 1986. Role of thought, sight, smell, and taste of food in the cephalic phase of gastric acid secretion in humans. Gastroenterology. 90 (2), 428–433.

Peschel, S.K.V., Feeling, N.R., Vögele, C., Kaess, M., Thayer, J.F., Koenig, J., 2016. A systematic review on heart rate variability in Bulimia Nervosa. Neurosci Biobehav Rev. 63, 78–97.

E. Lambert G. Lambert C. Ika-Sari T. Dawood K. Lee R. Chopra N. Straznicky N. Eikelis S. Drew A. Tilbrook J. Dixon M. Esler M.P. Schlaich 58 1 2011 43 50.

M.S.B. Huda H. Mani T. Dovey J.C.G. Halford E. Boyland C. Daousi J.P.H. Wilding J. Pinkney Ghrelin inhibits autonomic function in healthy controls, but has no effect on obese and vagotomized subjects 73 5 2010 678 685.

Monteleone, P., Serritella, C., Martiadis, V., Maj, M., 2008. Deranged secretion of ghrelin and obestatin in the cephalic phase of vagal stimulation in women with anorexia nervosa. Biol Psychiatry. 64 (11), 1005–1008.

Kwieciński, J., Konarski, J.M., Strzelczyk, R., Krzykała, M., Konarska, A., Bartkowiak, S., Lopes, V., Malina, R.M., 2018. Non-linear relationships between the BMI and physical fitness in Polish adolescents. Ann Hum Biol. 45 (5), 406–413.

Reginato, E., Azzolina, D., Folino, F., Valentini, R., Bendinelli, C., Gafare, C.E., Cainelli, E., Vedovelli, L., Iliceto, S., Gregori, D., Lorenzoni, G., 2020. Dietary and

Lifestyle Patterns are Associated with Heart Rate Variability. J Clin Med. 9 (4), 1121. https://doi.org/10.3390/jcm9041121.