The role of cardiac vagal tone and inhibitory control in pre-schoolers' listening comprehension

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Abstract

This study investigated the role of basal cardiac activity and inhibitory control at the beginning of the school year in predicting oral text comprehension at the end of the year in pre-schoolers. Cardiac activity at rest has been associated with cognitive performances in various tasks, as well as with inhibitory abilities. Moreover, text comprehension is linked with inhibition. Yet, no previous studies have assessed direct and interactive effects of inhibitory control and cardiac vagal tone in pre-schoolers' listening comprehension. Forty-four, 4-year-olds participated in the study. At the beginning of the school year children's electrocardiogram at rest was registered followed by the assessment of inhibitory control as well as verbal working memory and verbal ability. At the end of the year all children were administered a listening comprehension ability measure. A stepwise regression showed a significant effect of basal cardiac vagal tone in predicting listening comprehension together with inhibitory control and verbal ability No interaction was found. These results are among the first to show the predictive role of basal cardiac vagal tone and inhibitory control in pre-schoolers' oral text comprehension, and offer new insight into the association between autonomic regulation of the heart, inhibitory control, and cognitive activity at a young age.

Key words: cardiac vagal tone, pre-schoolers, listening comprehension, inhibitory control.

Introduction

Listening comprehension (i.e., comprehension of oral texts) is critical for language and literacy acquisition and thus has a significant role in predicting later learning ability and school success (e.g., Oakhill & Cain, 2007). It has been shown that listening comprehension during the preschool years predicts reading comprehension in primary and secondary school (e.g., Florit, Roch, & Levorato, 2014; Kim, 2016). Specifically, listening comprehension is a complex process that results in the construction of a coherent mental representation of the meaning of the text. This entails the processing of information at the word-, sentence-, and discourse-level that requires both general cognitive (such as memory and attention) and more specific language skills (e.g., Oakhill & Cain, 2007). In particular, the roles of verbal ability and working memory have been widely addressed in the literature. Verbal ability is necessary to understand the meaning of words and their relations; verbal working memory is needed to temporarily store and integrate linguistic information in texts (e.g., Florit et al., 2014; Kim, 2016). Evidence has shown that verbal ability, assessed through measures of receptive and expressive vocabulary, and working memory uniquely contribute to listening comprehension (Florit et al., 2014; Florit, Roch, Altoè, & Levorato, 2009; Kim, 2016).

Additional cognitive processes, however, are involved in the development of basic literacy skills in early childhood (e.g., Welsh, Nix, Blair, Bierman, & Nelson, 2010), such as working memory, attention control and inhibitory control. Inhibitory control is defined as the ability to suppress a dominant response and initiate a subdominant response. Data on the role of this competence in pre-schoolers' listening comprehension is still scarce, yet very promising. Kim and Phillips (2014) provided evidence that inhibitory control accounts for listening comprehension in children attending kindergarten and first grade from high-poverty schools. Specifically, inhibitory control uniquely contributed to listening comprehension, after accounting for age and expressive vocabulary. Studies on school-age children showed that inhibitory control predicts reading comprehension after controlling for working memory (Cantin, Gnaedinger, Gallaway, Hesson-McInnis, & Hund, 2016; Kieffer, Vukovic, & Berry, 2013). In the work of Kieffer et al. (2013), however, inhibitory control was not related to listening comprehension of short passages. Overall, further investigation on the role of inhibitory control in pre-schoolers' listening comprehension is needed.

Recently, a different line of studies has identified self-regulation skills as critical for children's adaptive functioning across various domains including cognitive/academic functioning (Graziano, Reavis, Keane, & Calkins, 2007). Given the importance of self-regulation for children's adaptive functioning, it is not surprising that researchers have attempted to identify biological markers associated with this ability. A key physiological correlate of children's ability to adapt to the environment and self-regulate (Porges, 2007) has been found in a fairly stable individual characteristic that is the parasympathetic dominance of the Autonomic Nervous System (ANS) at rest; here termed vagal tone (Li, Snieder, Su, Ding, Thayer, Treiber, & Wang, 2009). Resting cardiac vagal tone is thought to index the amount of regulatory resources available for a child to draw on during times of challenge. Higher vagal tone at rest indexes better cardiac flexibility and ability of the system to respond, and helps the child to self-regulate and better adapt to environment demands. Studies examining relations among cardiac vagal tone, emotionality, and development indicate that resting vagal tone is related to increased sociability, low levels of problem behaviour, and higher levels of cognitive developmental competences (Calkins, & Keane 2004; Suess, Porges, & Plude, 1994). For example, higher basal cardiac vagal tone predicted better performance on standardised scales assessing working memory and cognitive efficiency in school-age children (Staton, El-Sheikh, & Buckhalt, 2009).

The influence of vagal tone on the heart can be inferred through Heart Rate Variability (HRV), that is the physiological variation in the intervals between heart-beats. Even though cardiac vagal tone has been linked to both self-regulatory abilities and cognitive performance, there is only one study linking text comprehension with cardiac vagal tone. This study assessed the role of HRV in predicting reading achievement in school-age children (Becker et al., 2012). Findings however failed to show an effect of HRV at rest, whereas suppression of cardiac vagal tone in response to a challenge was found to be relevant for reading achievement. To our knowledge, no data are available on the role played by cardiac vagal tone in predicting listening comprehension in pre-schoolers. Yet, this is an encouraging field of study since it offers new insight into the association between cognitive activity and autonomic regulation of the heart as well as helps to identify fairly stable individual characteristics that may predict children's academic success. As a matter of fact, evidence suggests that measures of vagal tone on the heart at rest primarily represent a trait like biomarker of self-regulation (Bertsch, Hagemann, Naumann, Schächinger, & Schulz, 2012), and longitudinal studies have demonstrated the stability of HRV over time (Li et al., 2009).

Moreover, the ability to self-regulate has been linked with inhibitory control tasks, that is, individuals low on behavioural inhibition are also less capable to control their impulses and self-regulate than those high in inhibition (Hofmann, Schmeichel, & Baddeley, 2012). This is true also among preschool children (Carlson, & Wang, 2007). Interestingly, resting HRV has also been associated with inhibitory control as indicated by better performance on a number of cognitive, affective, and motor tasks (e.g., Gillie, Vasey, & Thayer, 2013, Hovland et al., 2013).

Hence, looking at the whole picture, it is well known that listening comprehension in pre-schoolers is of paramount importance for subsequent achievement and later school success (e.g., Oakhill & Cain, 2007). This competence has been linked not only to verbal ability but also to inhibitory control (Kim & Phillips, 2014). Furthermore, cardiac vagal tone at rest is considered an important biomarker of self-regulation (Thayer, et al, 2012) as well as strongly associated with cognitive abilities (Becker et al., 2012).

In the current study, we sought to extend the work in this area by testing the direct and interactive effects of inhibitory control and resting cardiac vagal tone on pre-schoolers' listening comprehension. Specifically, we assessed whether children's inhibitory control on a Stroop-like task and cardiac vagal tone during a 10-minutes resting session at the beginning of the school year predicted the performance on a listening story comprehension task at the end of the year while controlling for verbal working memory and vocabulary abilities. Moreover, we assessed the possible interactive effect of the main predictors. We expected that both greater vagal tone at rest and higher inhibitory control would be associated to a better listening comprehension in children. We also expected that the positive combined effects of the two factors would result in the best performance.

Method

Participants

Forty-three pre-schoolers (24 males, 55.8 %) with a mean age of 4.74 years (*SD* = 0.62) took part in the study. All children were attending a public pre-school in northeast Italy. Most children were from low-middle class families and reported a low (29.5%) or moderate (70%) score on the Family Affluence Scale (FAS; Boyce, Torsheim, Currie, & Zambon, 2006). Parental written permission and students' verbal assent were required for participation; in addition, written informed consent was obtained from the school principal.

Procedure

Children were tested in six sessions on different days. The first five sessions took place within two weeks at the beginning of the school year (October 2015). In the first session, their ECG was registered at rest, that is, while they were comfortably sitting and watching a relaxing video (duration 10 minutes) on a computer screen in a quiet room. During sessions two to five, children were tested individually on inhibitory control, verbal working memory, and language comprehension and production. Finally, listening comprehension was tested at the end of the school year (May 2016). It is important to note that children were familiar with the researcher that collected the data and were happy to join her for the individual sessions.

Measures

Listening Text Comprehension. It was assessed through an Italian test for listening comprehension, TOR 3–8 (Levorato & Roch, 2007), designed for children between 3 and 8 years. The test consists of two short stories of equal difficulty and length, which are read individually to each participant. Comprehension is evaluated using 10 questions per story, half of which are based on explicit information (factual questions), while the others require inferences to be generated (inferential questions). The questions are followed by a four multiple-choice task where children are asked to respond orally or by pointing to the corresponding picture. Each correct answer is given one point (range 0–20). Standardized scores were computed and used here (*M* = 10, *SD* = 2). The reliability for TOR 3–8, evaluated by calculating Cronbach's alpha over items of the stories, ranges from .62 to .72.

Inhibitory control. It was assessed via a Stroop type task-Day/night version (Gerstatd et al., 1994). In this task children are presented with 16 cards and asked to say "night" when they see a picture of the sun, and "day" when they see a picture of a moon and stars. Children are also given a control version of the task in which they are thought to associate two separate abstract drawings with the words day and night. The proportion of correct responses given in the control and experimental trial are considered as an indicator of inhibitory control.

Basal cardiac vagal tone. For the acquisition of the ECG signal a POLAR sensor was placed on the torax using a multi-modality physiological monitoring device that encodes biological signals in real-time (ProComp Infiniti, Thought Technology, Montreal, Canada). ECG signal was recorded via a 12-bit analog-to-digital converter with a sampling rate of 256 and stored sequentially for analysis for a duration of 10 minutes at rest. ECG signal was then exported in the Kubios-HRV 2.2 (Kuopio, Finland) software to estimate the occurrence of QRS complex and derive the inter-beat intervals calculated as differences between successive R-waves occurrence times. The ECG signal was visually inspected and, in order to correct for artefacts a piecewise cubic splines interpolation method that generates missing or corrupted values into the IBI series. Then, square root of the mean squared differences (rMSSD) of successive heart periods was calculated. Specifically, as an index of the variation in the interbeat intervals, rMSSD is sensitive to short-term heart period fluctuations, thus it is thought to specifically reflect the parasympathetic activity through the influence of vagal nerve on the heart (Berntson et al., 1997).

Control variables

Verbal working memory. It was assessed through the verbal dual task (Lanfranchi, Cornoldi, & Vianello, 2004). In this task the child is presented orally with a list of two to five words and asked to remember the first word on the list and to tap on the table when the word ball is presented (i.e., once in every list). The score of 1 was given each time the child both remembered the first word of the list and performed the tapping task. Otherwise, the score of 0 was given. In each task, the minimum score was 0 and the maximum score was 8.

Verbal ability. It was assessed through two tests: 1) The vocabulary subtest of the Wechsler intelligence scale for preschool and primary school (Italian adaptation by Sannio Fancello, & Cianchetti, 2008) allowed to assess children's expressive vocabulary; 2) the Peabody picture vocabulary test-revised (Italian adaptation by Stella, Pizzoli, & Tressoldi, 2000) evaluated receptive vocabulary. A composite verbal ability score was computed using the mean of the standardized scores (i.e., *z* scores) obtained by children in the two scales.

Results

Descriptive statistics of the studied variables and bivariate correlations are presented in Table 1. A series of t-tests examined if there were gender differences for listening comprehension, baseline rMSSD, and inhibitory control. All tests were non-significant.

As displayed in Table 1 the majority of measures registered at the beginning of the school year showed significant correlations with listening comprehension; cardiac vagal tone, inhibitory control, and verbal ability showed the highest correlation coefficients. To identify which measures, registered at the beginning of the year, made the largest contribution in predicting children's listening comprehension at the end of the school, we performed a stepwise linear regression analysis (see Table 2). In the first step children's cardiac vagal tone, inhibitory control, verbal ability, verbal working memory, and age (months) were entered in the regression equation as predictors, whereas in the second step also the interaction between rMSSD and inhibitory control was considered. We found that rMSSD, inhibitory control, and verbal ability entered the equation (Table 2). Specifically, children's cardiac vagal tone was a significant predictor of the participants' listening comprehension, R^2 = .27, F_{change} (1,41) = 14.97, p < .001, accounting for 27% of the variance. Inhibitory control resulted in a statistically significant increase in the explained variance, R^2 = .37, F_{change} (2,41) = 6.50, p =.015, while accounting for 10.2% of the variance. Verbal ability albeit included in the model, R^2 = .43, F_{change} (3,41) = 4.43, p =.042, accounted only for 6.4% of the variance. The interaction between inhibitory control and rMSSD, as well as verbal working memory and age were non-significant and did not enter the model.

Discussion

To our knowledge, this is the first study investigating the contribution of both resting cardiac vagal tone and inhibitory control in predicting pre-schoolers' listening comprehension. Two key findings emerged. First, the unique role of vagal tone activity on the heart in predicting listening comprehension in pre-schoolers. Second, the existence of a link between inhibitory control and text comprehension was confirmed (Kim & Phillips, 2014).

In relation to the first finding, our data suggest that in addition to linguistic and cognitive components, cardiac vagal tone is a plausible mechanism, accounting for the reciprocal relations between self-regulatory abilities and academic functioning. Whereas the role of verbal ability in influencing comprehension has been widely reported at this age (e.g. Florit et al., 2014; Kim, 2016), research addressing children's individual characteristics on trait like biomarkers is still scarce. The present work adds to data on the association between cardiac vagal tone and listening comprehension, strengthening the idea that higher levels of basal cardiac vagal tone are a good indicator of children better functioning in several domains including literacy acquisition, and school success. The only previous study investigating the relationship between HRV and listening comprehension failed to find an association between HRV at rest and listening comprehension (Becker et al., 2012). Still, methodological issue may account for this difference in results. Becker et al., (2012) used a very short recording of electrocardiographic activity (1 minutes) while the minimum duration recommended by guidelines (Bernston et al., 1997; Task Force, 1996) is 5 minutes. In the present study 10 minutes of electrocardiographic activity was recorded, in order to obtain a reliable index of parasympathetic activity on the heart at rest.

The characteristic of cardiac vagal tone to restore and conserve energy at rest is an essential mechanism that represents a fairly stable characteristic of how the individual self-regulate and respond to challenges (Li, et al 2009; Porges 2007). However there are promising techniques that allow learning how to better self-regulate and even modulate basal cardiac vagal tone (Prinsloo, Rauch, Lambert, Muench, Noakes, & Derman, 2011). Given the importance of cardiac vagal tone for early academic success it may be worth monitoring such activity at an early age and implementing interventions to improve self-regulation in more at risk children.

In relation to our second finding, as expected, listening comprehension was predicted by pre-schoolers' performance in the inhibitory control task at the beginning of the year. Since inhibitory control facilitates the ability to resist distraction and sustain focused concentration, it is reasonable to expect its relation to oral language performance at a young age. Confirming previous findings on pre-schoolers' (Kim & Phillips, 2014), we found that children's good performance on the Stroop-like task in September predicted a better comprehension at the end of the school year (in May). Moreover, such ability when combined to higher cardiac vagal tone at rest explained a greater portion of the variance in predicting pre-schoolers' oral text comprehension. Inhibitory control is part of self-regulatory executive functioning and this capacity is related to activity in the prefrontal areas of the brain, which have been also hypothesized to be involved in the control of cardiac vagal tone (e.g., Thayer et al., 2012). This is confirmed in our data by the positive correlation between vagal tone on the heart (as measured by rMSSD) at rest and the performance in the inhibitory control task. This is also in line with recent findings on adults, showing an association between greater inhibitory control and higher basal HRV (e.g., Thayer et al., 2012).

Moreover, data on infants supports the notion that higher levels of resting cardiac vagal control reflect more effective regulation of both attention and emotion during early childhood (Gueron-Sela et al., 2016). Given the link between inhibitory control and cardiac vagal tone, we tested the possible interaction of these two factors in predicting comprehension of oral texts. Yet, contrary to our expectations, the interaction between cardiac vagal tone and inhibitory control did not enter the model and hence did not significantly influence text comprehension. One explanation may be that even if these two factors are related, they give unique contribution to children's ability to listen carefully and understand a story that is being read to them. In other words, they both significantly contribute to a child's ability on a listening comprehension task, but do not interact with one another.

These finding, however, should be taken with caution since the study has a number of limitations. The main issue is related to the limited number of children included in the study which did not allow to control for a number of possible other variables which may influence listening comprehension (Kim & Phillips, 2014). Specifically, further studies should include the assessment of other individual characteristics (e.g., temperament), environmental factors (e.g., parenting styles, Howse, Calkins, Anastopoulos, Keane, & Shelton, 2003) and cognitive variables (Young-Suk & Grace Kim, 2016) that may enter the equation. A second issue is the lack of the measurement of listening comprehension skills at the beginning of the school year that would have allowed a better understanding of the data. Yet, children were already assessed on several domains and a selection of assessments had to be made in order not to overburden them.

Despite these caveats the present study adds to the literature by giving some important theoretical hints on the predictive role of cardiac vagal tone and inhibitory abilities on listening comprehension in pre-schoolers. Our findings have also significant implications for both educational and clinical practice. That is, interventions taking into account individual differences and aiming at the improvement of self -regulation skills and inhibitory control are recommended. Specifically, since a growing number of empirical studies have documented the effectiveness of bio-behavioral techniques (such as biofeedback) to self-regulate individuals' psychophysiological activity (cardiac vagal tone), these practices could also be usefully implemented at an early age.

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Table 1

Descriptive Statistics and Correlations for Listening Comprehension, rMSSD, Inhibitory Control and all Control Variables (N=43)

	2	3	4	5	6	7	*M*	*SD*
1. Age (months)	.05	.04	-.22	.29*	.46**	.42**	56.93	7.04
2. Listening comprehension		.52***	.51***	.57***	.56***	.23*	10.67	1.85
3. rMSSD			.43**	.17	.17	.24*	52.28	23.52
4. Inhibitory control				.04	.14	.15	1.63	1.03
5. Expressive vocabulary					.75***	.49***	17.98	6.09
6. Receptive vocabulary						.44**	69.07	22.01
7. Verbal working memory							3.62	2.54

Note. *$p < .05$; **$p < .01$; ***$p < .001$

[a] In subsequent analyses *z* scores were calculated for these two scales to create a composite verbal ability score.

Table 2

Summary of Stepwise Regression Analysis for Variables Predicting Listening Comprehension

Model	B^a	*SE*	*β*	*t*	*F*	R^2	ΔR^2
1					14.97	.27	.27
rMSSD	.04	.01	.52	3.87***			
2					11.74	.37	.10
rMSSD	.03	.01	.36	2.60**			
Inhibitory Control	.35	.14	.35	2.55**			
3					9.97	.43	.06
rMSSD	.03	.01	.32	2.39*			
Inhibitory Control	.34	.13	.33	2.49*			
Verbal Ability	.53	.25	.26	2.11*			
N	43						

Note. [a] Unstandardized coefficient.

* $p < .05$ ** $p < .01$, *** $p < .001$