



# Tonic and phasic co-variation of peripheral arousal indices in infants



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## ABSTRACT

Tonic and phasic differences in peripheral autonomic nervous system (ANS) indicators strongly predict differences in attention and emotion regulation in developmental populations. However, virtually all previous research has been based on individual ANS measures, which poses a variety of conceptual and methodological challenges to comparing results across studies. Here we recorded heart rate, electrodermal activity (EDA), pupil size, head movement velocity and peripheral accelerometry concurrently while a cohort of 37 typical 12-month-old infants completed a mixed assessment battery lasting approximately 20 min per participant. We analysed covariation of these autonomic indices in three ways: first, tonic (baseline) arousal; second, co-variation in spontaneous (phasic) changes during testing; third, phasic co-variation relative to an external stimulus event. We found that heart rate, head velocity and peripheral accelerometry showed strong positive co-variation across all three analyses. EDA showed no co-variation in tonic activity levels but did show phasic positive co-variation with other measures, that appeared limited to sections of high but not low general arousal. Tonic pupil size showed significant positive covariation, but phasic pupil changes were inconsistent. We conclude that: (i) there is high covariation between autonomic indices in infants, but that EDA may only be sensitive at extreme arousal levels, (ii) that tonic pupil size covaries with other indices, but does not show predicted patterns of phasic change and (iii) that motor activity appears to be a good proxy measure of ANS activity. The strongest patterns of covariation were observed using epoch durations of 40 s per epoch, although significant covariation between indices was also observed using shorter epochs (1 and 5 s).

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## 1. Introduction

Neural control of the autonomic nervous system (ANS) is thought to originate in the brain stem and hypothalamus. The hypothalamus, just above the brain stem, acts as an integrator for autonomic functions, and receives input from upstream cortical areas such as the insular cortex and limbic systems (Cechetto & Chen, 1990; Ulrich-Lai & Herman, 2009). Regulation of ANS function also involves homeostatic feedback loops involving endocrine as well as neural systems, such as the hypothalamic–pituitary–adrenal axis (Tsigos & Chrousos, 2002).

Direct measurement of ANS activity, such as single cell recording from brainstem synapses, is common in animal research (Aston-Jones, Rajkowski, & Cohen, 1999; Usher, Cohen, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999) but is not possible in humans. Almost all research with humans, therefore, has used one of several peripheral indices of ANS activity—such as heart rate, movement

patterns, electrodermal activity (EDA), pupil size, EEG or salivary cortisol.

Research into how activity on these peripheral indices relates to behaviours such as attention or emotion reactivity has a long history (Broadhurst, 1957; Yerkes & Dodson, 1908). For example, better learning has been associated with increased event-related heart rate (Linnemeyer & Porges, 1986) and electrodermal activity (EDA) changes (Brown, 1937). However, the majority of previous psychophysiological research examines relations between a single measure of peripheral autonomic activity and a behavioral measure. Research that compares across measures is relatively rare. However, such comparisons are important because different measures of arousal may have different properties and may not be interchangeable. Each of the peripheral systems is responsible for multiple functions, and whereas some peripheral autonomic systems are influenced mainly by the sympathetic branch of ANS, others are innervated by both sympathetic and parasympathetic branches (McCabe, Schneiderman, & Field, 2000; Shields, Macdowell, Fairchild, & Campbell, 1987). Pupil size, for example, is associated with both the sympathetic and parasympathetic nervous systems (Koss, 1986), but also has contributions from the sensory nervous system (Hess & Polt, 1960; Loewenfeld, 1993).

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For this reason, the relationships between different widely used indices of ANS activity are unlikely to be simple one-to-one correspondences. Previous research has found contradictory results regarding the co-variation across indices of peripheral arousal. In some studies various indicators of arousal fail to show reliable correlations with one another (Lacey, 1967; Loewenfeld, 1993; Sanders, 1983; Taylor & Epstein, 1967). For example, Loewenfeld noted in adults that correlations between pupillary dilations and other indices of autonomic function (e.g. heart rate, electrodermal activity) are not high (Loewenfeld, 1993), and other authors reported that heart rate and skin conductance do not co-vary (Taylor & Epstein, 1967). Others have reported consistent results across measures of peripheral arousal: for example, Kahneman, Tursky, Shapiro, and Crider (1969) observed consistent changes in pupillary diameter, heart rate and skin resistance during information intake and processing in typical undergraduates.

To our knowledge, no previous research has investigated whether the covariation of peripheral ANS indices may be higher in infants and children than in adults. Neural responses are generally thought to become increasingly fractionated and differentiated with increasing age, as cortical specialisation develops (Johnson, 2010). It is possible that autonomic responses may also become increasingly differentiated with increasing age. Alternatively, given that autonomic responses are controlled mainly from the brainstem, which becomes mature earlier than other areas of the brain (Deoni et al., 2011; Gogtay et al., 2004; Paus et al., 2001), it is possible that this is not the case.

However, one further potential reason for these inconsistencies in the adult literature is that previous studies fail to account for the temporal dynamics of arousal activity. The papers cited above have generally examined average changes in arousing experimental conditions, controlling for baseline activity levels on a per-individual basis. However, the timing between dimensions of arousal activity may differ in a number of different ways. First, the different dimensions of peripheral arousal may differ in the time-course of their relative onset and fluctuations. For example, EDA increases following an arousing stimulus are slow and are typically detectable on a scale of seconds (e.g. Kylliäinen et al., 2012), whereas changes in motor activity are detectable on a millisecond scale (e.g. Robertson & Johnson, 2009).

Relatedly, they may also differ with respect to the tonic and phasic components of their activity. Tonic activation refers to shifts in the overall baseline of activity, whereas phasic activity refers to fluctuations over time, which may occur spontaneously or in response to an event. Evidence from research on EDA indicates that tonic and phasic components of the autonomic response may rely on different neural mechanisms (Hazlett, Dawson, Schell, & Nuechterlein, 2001; Nagai, Critchley, Featherstone, Trimble, & Dolan, 2004), indicating that these should be studied separately. Additionally, tonic and phasic activity may interact, such that phasic responses may only occur at certain tonic levels of arousal activity. For example, Aston-Jones and Cohen (2005) examined firing rates within individual cells in the brainstem of human primates (thought to be responsible for regulating ANS function) and reported that high and low levels of tonic activity within the brainstem were associated with fewer distinct phasic responses, whereas mid-level tonic activity was associated with larger phasic responses (Usher et al., 1999). Finally, some signals may be much more sensitive indices of even minor increases in overall arousal, whereas other measures may only show measurable responses after a higher threshold of arousal.

From a conceptual perspective, differences among dimensions of autonomic activity might be useful for characterizing individual differences in autonomic and cardiac control (Berntson, Cacioppo, Quigley, & Fabro, 1994; Cacioppo, Tassinary, Berntson, 2000). From a methodological perspective, these temporal differences suggest

different potential uses, or different recommendations for what measure to use within a particular study. Thus, it is interesting and relevant to look at the co-variation across measures of arousal, considering multiple timescales of average or baseline activity as well as potential task-related changes.

The aim of the present paper, therefore, is to examine co-variation in peripheral arousal indices in infants. We will consider the activity of five indices of sympathetic arousal activity: heart rate, electrodermal activity, pupil size, and two measures of motor activity, collected from the head and foot. Our analyses consider multiple timescales of activity as well as potential task-related changes. For each measure, we first give a brief description of the system activation in the brainstem, as well as examples from past work used to validate these measures of arousal from both social-emotional and cognitive domains.

### 1.1. Heart rate (HR)

Neural control over heart rate is complex, involving both neural and endocrine systems (Cacioppo et al., 2000). Both the sympathetic and parasympathetic nervous systems are involved in regulating heart rate (McCabe et al., 2000). Infant heart beats occur at a timescale of approximately 120 beats per min (i.e., 2 Hz), which is markedly higher than that found in adults. In infants, heart rate changes phasically in response to social and non-social stressors (Morasch & Bell, 2012) and levels can reduce following calming stimuli such as breast feeding or swaddling (Campos, 1989). Most studies assess changes in heart rate in the timescale of seconds, comparing overall phasic HR changes relative to baseline across stress and non-stress conditions (Alkon et al., 2006). However, a number of studies have also identified reliable phasic HR changes occurring within seconds. For example, temporary HR increases in response to an oncoming stranger can be observed within a few beats (Waters, Matas, & Sroufe, 1975), and phasic changes during periods of gaze aversion are observed within a similar timeframe (Field, 1981). A number of studies have examined individual differences in tonic heart rate. For example, Gower and Crick (2011) found that lower baseline heart rate was associated with increased engagement in classroom aggression in preschool children.

Parasympathetic influences on heart rate are also thought to underlie phasic decelerations of heart rate following attention to a stimulus (Porges, 2007). Across a number of studies, Richards (2011) have studied phasic heart rate changes relative to individual looks in infants. They have shown, for example, that infants are less distractible during periods of temporarily lowered heart rate (Casey & Richards, 1988; Lansink & Richards, 1997), and that objects presented during periods of temporarily lower heart rate are remembered better (Richards, 1997). One further measure of parasympathetic influences on heart rate, which for reasons of space we do not include in the present paper, is respiratory sinus arrhythmia (RSA). This refers to periodic fluctuations timed with respiration cycles, and is thought to be mediated by the parasympathetic system (Alkon et al., 2006; Porges, 2007; Richards, 1985b).

### 1.2. Electrodermal activity (EDA)

Electrodermal activity is widely used as a peripheral index of arousal in adult research (Cacioppo et al., 2000). EDA measures activity of sweat glands, under control of the sympathetic nervous system (Shields et al., 1987). Repeated administration of a stressor leads to phasic increases in EDA levels, a gradual reversal in the usual decline over time in EDA, as well as an increase in the frequency of spontaneous (non-event-locked) phasic changes in EDA (Bohlin, 1976). Valid phasic event-related changes in EDA are thought to begin a minimum of 1–3 s and a maximum of 8–10 s after an event, and maximum height of the response can occur as late as

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