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MEASURING THE AUTONOMIC NERVOUS SYSTEM AS A WINDOW INTO THE MIND AND BRAIN: A SELECTIVE REVIEW

Introduction

The ancient Greeks already claimed the relation between the brain and psychological and physiological states. Aristotle (BC 384–322) argued that the heart was the centre of the psychophysiological system and the brain function existed to cool the blood arising from the heat and seething of the heart (Smith, 2013). Since the 1990s, brain imaging technologies have advanced both in hardware (e.g. functional magnetic resonance imaging: fMRI) and software (e.g. machine learning). Subsequently, brain mapping of cognitive functions has rapidly progressed and neural substrates of cognition have been clarified and brain imaging techniques have been widely used to investigate internal processes in psychological research. However, measures of the autonomic nervous system (ANS) remain commonly used to investigate internal states behind cognitive processes and psychological states. How do these psychological studies use ANS measurements? Are there specific suitable ANS measurements depending on the psychological function to be examined? This paper summarises the characteristics of each ANS measurement predominantly used in psychological studies. In addition, it reviews the results of recent literature which has investigated core topics in psychophysiology such as attention and emotion recognition. Finally, the strengths of ANS measurements are summarised compared to brain imaging techniques. As the aim of this paper is to broadly communicate the utility of the ANS measures to psychologists who are not familiar to use them, this paper focuses on recent results of psychophysiological studies and details to each topic such as mechanisms will be limited. If the research area has recently been the subject of a meta-analysis or systematic review, the empirical studies cited in the meta-analysis or review are introduced. Apart from references to the history of the method, the literature was mainly selected from 2010 to 2021. Searches were conducted in PsychArticles databases. The search strategy was as follows: (“heart rate” OR “skin conductance” OR “pupil” OR “eye blink” AND “attention” OR “cognitive load” OR “cognitive effort” OR “emotion” OR “stress” OR “reward” AND Peer-Reviewed Journals only AND Year 2010 To 2021). This search found 248 papers including the terms in the abstract. Then, the papers are reviewed and assessed for their relevance to each topic. The results of 63 empirical papers are introduced (Table 1-3). Psychophysiological research has a long history and various studies have been conducted, sometimes showing controversial results. It is important to note that what can be presented in this paper is only a small number of empirical studies and this is not a meta-analysis, so it is not intended to dismiss other results.

What is indexed in ANS measurements?

Many psychological studies using physiological methods measure activations in the ANS. The ANS represents the principal neural channels through which the brain and internal bodily organs interact (Brading, 1999). Sympathetic and parasympathetic nervous systems (branches of the ANS) regulate vegetative autoregulatory processes in the human body and responses elicited by dynamic interactions with the environment (Critchley, 2009). The balance of activations in the sympathetic and parasympathetic nervous systems modulates physiological responses such as pupil dilation and heart rate increase (Karemaker, 2017). The sympathetic nervous system is responsible for the ‘fight or flight’ response—an automatic physiological reaction to a harmful or stressful event, preparing the animal for fighting or fleeing (Jansen et al., 1995). The sympathetic nervous system works facilitatively, and sympathetic fibres use the neurotransmitter noradrenaline to dilate the pupil, increase the skin sweat and raise the heart rate. In contrast, the parasympathetic fibres typically work inhibitory, with acetylcholine as the main neurotransmitter to contract the pupil and decrease the skin sweat and heart rate. The influence of these two systems, sympathetic and parasympathetic systems, on organs does not on a single continuum. It has been shown that these systems function independently and the activity of sympathetic and parasympathetic nervous systems are not reciprocal (Cacioppo, Uchino, & Berntson, 1994; Berntson et al., 1991). In other words, the sympathetic and parasympathetic nervous systems are not on one axis, but two axes of activity determine the effects on organs.

In the regulation of the ANS, there are two important processes: homeostasis and allostasis. Homoeostasis is defined as the ability of an organism to maintain the internal environment of the body within limits that allow it to survive (McEwen, 2016). Due to homeostasis, it has been claimed that motivations arise from the physiological need to maintain the internal environment of the body, and cognitive processing of external stimuli and behavioural reactions to the surrounding environment can be modulated by physiological states (Critchley, 2009). Homeostasis is described as stability through constancy, while allostasis is defined as achieving stability through change (Sterling & Eyer, 1988). Allostasis is the adaptive process of an organism to change the defended levels of one or more regulated parameters as needed to adjust to new or changing environments. For example, an elevated level of heart rate is maintained in a stressful environment relative to the level maintained in a less-stressful environment. Homeostasis and allostasis ate complementary rather than exclusive each other. To maintain the internal environment of the body and adaptively respond to the external environment, both types of control are needed (Schulkin & Sterling, 2019). For an overview of the mechanisms of homeostasis and allostasis, see the Handbook of Psychophysiology (Cacioppo, Tassinary, Berntson, 2007).

Characteristics of each measurement

Figure 1 shows how the activities in the ANS are reflected in each measure. However, can these measurements be used to investigate psychological processing in the same way?

Heart rate and heart rate variability. Heart rate refers to the number of times that the heart muscle contracts or beats, usually measured by Ag/AgCl electrodes of electrocardiogram (ECG). Heart rate is calculated by the standard measure of beats per minute (bpm), averaged heart rate in a specific period. The normal resting adult human heart rate is 60–100 bpm (American Heart Association), thus a minimum sampling frequency of 500 Hz may be required to detect the R-spikes. Heart rate measurement has started to be used in psychophysiology since the late 1950s, investigating the relationship between ANS responses and cognitive processing (e.g. Lacey, 1959). Heart rate variability (HRV) has been well examined since 1996 when a standard was established and parameters defined (Malik et al., 1996; Berntson, 1997). HRV is defined as the beat-to-beat variation in heart rate, and it has become a popular clinical and psychological investigational tool (Billman, 2011). HRV has been widely used to investigate autonomic cardiovascular control and/or target function impairment (Montano et al., 2009). In these studies, HRV has been assessed by time domain and frequency domain metrics (for more details see Shaffer & Ginsberg, 2017). Time domain metrics are calculated by the variance among heart periods, the variance of the differences among heart periods, and the shape characteristics of heart period distributions. Frequency domain metrics are calculated by decomposing the overall heart period variance into specifiable frequency bands. The oscillatory components of HRV are typically differentiated into various spectral profiles, primarily separated into low frequencies (LF; 0.04–0.15 Hz) and high frequencies (HF; 0.15–0.40 Hz). It has been suggested that the LF reflect the cardiac outflow influenced by both sympathetic and parasympathetic nervous systems, while the HF can index cardiac parasympathetic tone (Laborde et al., 2017; Reyes del Paso et al., 2013).

The temporal resolution of the heart rate measurement is flexible, and studies using heart rate as an index of event-related ANS activities have shown that heart rate increase can be measured in a couple of seconds (2–3 s; Wascher et al., 2009; Ishikawa & Itakura, 2019; Ishikawa et al., 2022). In general, HRV can be measured over shorter (e.g. 5–10 min) or longer (12 or 24 h) periods (Ernst, 2017). However, longer recording epochs include slower fluctuations such as circadian rhythms and the cardiovascular system’s response to a wider range of environmental stimuli, short-term and long-term HRVs are not interchangeable with each other (Shaffer & Ginsberg, 2017). On the other hand, the short-term recording includes the effects of respiratory sinus arrhythmia (RSA), the respiration-driven speeding and slowing of the heart via the vagus nerve (Karemaker, 2009).

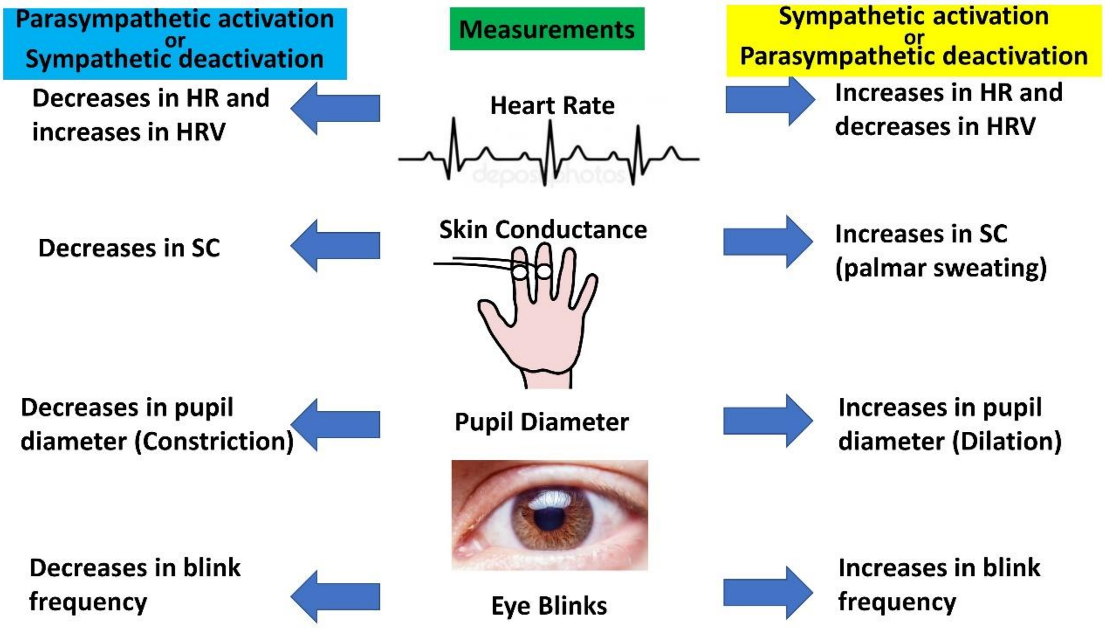

Figure 1. The autonomic nervous system functions indexed by each measure.

Skin conductance. Simultaneously with HR growth, other ANS measurements such as skin conductance (SC) and pupil diameter began to be used in psychological studies.

Initially, SC was used simultaneously with HR to test the consistency of ANS responses (Campos & Johnson, 1966; Johnson & Campos, 1967). The measurement of SC in psychological research was standardised in 1971 (Lykken, & Venables, 1971), and the terminology was defined; skin conductance level (SCL): tonic levels of conductance or resistance; skin conductance response (SCR) or galvanic skin response: phasic, usually elicited by an event, increase in SC. As a common term for all electrical phenomena in the skin, electrodermal activity (EDA) has also been used. SC has been used as an index of changes in sympathetic arousal that are tractable to emotional and cognitive states as it is the only autonomic psychophysiological variable that is not contaminated by parasympathetic activity (Braithwaite et al., 2013). The levels of SCR to a visual stimulus can reach the maximum within two seconds and no effects of the presentation time of the stimulus on the averaged SCR between two and five seconds (Helminen, Kaasinen, &

Hietanen, 2011). In addition, SCL slowly returns to baseline after reaching a peak (Breska, Maoz, & Ben-Shakhar, 2011). Around 20 years ago, interstimulus intervals (ISIs) for SCR measurement ranged between 20–60 s (e.g. Dawson, Schell, & Filion, 2000). Advances in deconvolution techniques have contributed to detecting SCRs even at ISIs as short as 3 s (Bach et al., 2010). Breska et al. (2011) compared SCRs between the long ISI ranging from 16 s to 24 s and the short ISI ranging from 8 s to 12 s. There was no effect of ISI on the differential skin conductance responses to the stimuli and nearly identical detection efficiency was observed in both ISI conditions. For more details on deconvolution and analysis methods, Kuhn et al. (2022) has summarised seven different approaches used in the literature on SCR.

Pupil dilation and eye blinks. Although pupil dilation has been investigated since the early 1960s (Hess & Polt, 1964; Kahneman & Beatty, 1966), pupillometry research has improved in the last two decades. The pupil diameter has been measured to investigate hedonic valence and emotional arousal during the presentation of visual stimuli (Bradley et al., 2008). Due to the advancement of eye-tracking technology, pupil dilation is relatively easy to study compared to the early studies. Recent eye trackers typically provide high temporal resolution (e.g. Tobii Pro Spectrum: Maximum 1200 Hz; EyeLink 1000 Plus: Maximum 2000 Hz) and can detect minor changes in pupil diameter (0.01 mm). The pupil size changes in response to an event or stimulus and peaks after approximately 1 s, with higher temporal resolution than HR and SCR (Stefan et al., 2012). The pupil size is affected by the brightness of visual stimuli; thus it is necessary to measure baseline pupil size and compare to evoked changes in pupil diameter to interpret cognitive processing (Joshi & Gold, 2020).

Eye blinks have also been measured since the 1970s (Graham, Putnam, & Leavitt, 1975). In human adults, spontaneous eye blinks appear every 3–5 seconds, with an average eye blink rate (EBR) of 20 blinks per minute, although with a large inter-individual variability (Nakano, 2017; Nakano, 2015). The eye blink duration is 50–500 ms (Caffier, Erdmann, & Ullsperger, 2003). Most psychophysiological studies measuring eye measures have used eye blink magnitude or amplitude as an index of startle reactions, rather than eye blink rate (Ventura - Bort et al., 2022). The startle blink response has been assumed as a defensive reflex and mainly used to investigate affective responses (Bradley, Codispoti, & Lang, 2006). As the research topic is limited, we focus on the blink rate rather than the startle responses.

Psychological studies using ANS measurements

How have these ANS measurements been used to investigate the human cognitive process and psychological states? This section introduces recent results of psychophysiological studies using ANS measurements in some core topics of psychology. Tables show the summary of studies introduced in this section (Table 1: HR; Table 2: SC; Table 3: eye measures).

Attention. The Aston–Jones model of attention states that animals are relatively less sensitive and unresponsive to changes in external stimuli at very low levels of arousal. However, they are more sensitive and responsive to peripheral stimuli at high levels of arousal (Aston–Jones, Chiang, & Alexinsky, 1991; Aston–Jones, Rajkowski, & Cohen, 1999). In particular, physiological arousal modulates to maintain visual attention focusing on a central target stimulus even in the presence of peripheral distractors (Aston–Jones & Cohen, 2005; Rajkowski, Kubiak, & Aston–Jones, 1994). Some studies have shown that increases in physiological arousal measured by heart rate correspond to a more vigilant visual attention indexed by short look durations (Wass, Clackson, & de Barbaro, 2016; de Barbaro, Clackson, & Wass, 2017). However, many recent studies have examined the correlation between HRV and attention. Resting-state HRV indexed by RMSSD (defined as root-mean square differences of successive R-R intervals) has been known to be associated with attention (Siennicka et al., 2019). It has been shown that individual differences in resting

HRV indexed by RMSSD predict the capacity to control attention while exposed to emotional stimuli (Appelhans & Luecken, 2006; Park et al., 2012). In these studies, individuals with low levels of HRV demonstrated significantly worse performance to maintain attention when distracted by fearful faces. Furthermore, other studies have indicated that individuals with high levels of HRV demonstrated greater attention over the distractors (Park et al., 2013a, Park et al., 2013b). It has been suggested that parasympathetic arousal, characterised by decreased HR and greater HF-HRV in resting states, is associated with attention maintenance (Thayer et al., 2009; Siennicka et al., 2019; Barber et al., 2020). Attention responding to external stimuli is associated with increases in HR, while decreases in HR have been observed during sustaining attention (Petrie et al., 2012; Tonnsen et al., 2018; Cobos et al., 2019).

A study examining the influence of attention levels on psychophysiological responses measured EEG, HRV, respiration rate, eye blinks and SCL during the low visual attentional task and high visual attentional task (Chang & Huang, 2012). The results suggested that EEG such as theta synchronization and LF-HRV during the task are correlated with attentional investment, while other measures did not indicate a significant change when the participants' attention levels increased. Thus, HR measurements would have a high sensitivity to index attentional levels.

Studies with HR measures have suggested that parasympathetic arousal is associated with attention, however, pupillometry studies have shown pupil dilation with enhanced attention.

Pupil dilations can index attentional effort (Smallwood et al. 2011; Kang, Huffer, & Wheatley, 2014). A possible explanation is that maintaining visual attention requires selecting a target. Pupil dilation reflects levels of noradrenaline (NA) released from the locus coeruleus (LC). The LC–NA complex is involved in behavioural selections, optimising the balance between exploitation (continue what you are doing) and exploration (disengage and choose between one of the alternative possibilities; Devilbiss, Page, Waterhouse, 2006).

Therefore, it has been suggested that attention maintenance is a perceptual selection as in behavioural decision-making, which can be related to the LC–NA complex indexed by pupil dilation. Other studies have also suggested that visual attention is an outcome of behavioural selection. For example, pre-stimulus pupil dilation correlated with the preparatory control of attention (Irons, Jeon, & Leber, 2017) and individual differences in temporal selective attention are predicted by pupil dilation (Willems, Herdzin, & Martens, 2015). SCL and SCR had been used in early studies before 2010 (e.g. Frith & Allen, 1983; Codispoti, & De Cesarei, 2007), however, recent studies have not used them to investigate attention.

Information process. A recent meta-analysis investigated the validity of ANS measures to index cognitive load (Ayres et al., 2021). It included 33 studies over five years (2016–2020) and found that eye measures such as pupil diameter and blinks were more sensitive than other physiological measures (heart rate, skin conductance, EEG). Therefore, we focus on the studies using pupil diameter and blinks for the index of cognitive load. Also, van der Wel & Steenbergen (2018) has reviewed studies on task-evoked pupil dilation measuring effort in cognitive control tasks.

The noradrenergic system has been suggested to influence the maintenance of appropriate levels of arousal for cognitive performance (Sara, 2009). Thus, pupil dilations are believed to reflect changes in mental effort. The early pupillometry studies reported that the pupil diameter is larger under conditions of higher attentional allocation or memory use, suggesting that pupil dilation can index cognitive load (Beatty, 1982). In the studies requiring participants to recall numbers of digits, larger numbers of digits induced greater pupil dilations (e.g. Granholm et al., 1996). In addition, in cognitive control tasks requiring switching and inhibition, pupil dilation responds to changes in task demands. This suggests that pupil dilation can be used as an index of cognitive effort (van der Wel & van Steenbergen, 2018). Pupil diameter can index cognitive load in both processes of auditory and visual information (Klingner, Tversky, & Hanrahan, 2011).

The measure of eye blinks is another robust index of cognitive load. The number of eye blinks increases in the task demanding high cognitive load (Ohira, 1996) or during information processing (Ichikawa & Ohira, 2004). In the auditory task, the EBR increases as a function of cognitive load (Magliacano et al., 2020). In addition, blinks occur during sensory processing and following sustained information processing (Siegle, Ichikawa, & Steinhauer, 2008). However, other studies have reported that eye blinks are suppressed during the task with high cognitive load, and the results of eye blinks are controversial. For example, Oh and colleagues (Oh, Jeong, & Jeong, 2012) showed that eye blinks were increasingly suppressed as the task difficulty increased. The suppression of eye blinks has been observed in tasks with high cognitive demands (Maffei & Angrilli, 2018; Hoppe et al., 2018; Ranti et al. 2020). It is suggested that, during a high cognitive load demanding visual task, the blinking behaviour might be reduced in order to avoid the loss of important information (Nakano et al., 2009). Thus, task type may affect the results of eye blinks whether the tasks require visual information keeping eyes opened.

Emotion recognition. Porges' polyvagal theory (Porges, 2007) proposes that the mammalian ANS has evolved to support survival, especially for social engagement. The ANS is influential in the recognition of facial expressions and inferring the mental states of other people (Appelhans & Luecken, 2006). The majority of psychophysiological studies have indicated strong links between ANS measurements and emotion recognition.

Studies of HRV have been well-examined in the last decade. For example, HF-HRV during resting is positively associated with performance on the emotion recognition task (Quintan et al., 2012). In addition, Quintana and colleagues controlled a variety of confounding variables affecting resting HRV – gender, body mass, smoking habits, physical activity levels, depression, anxiety and stress – however, the correlation between HRV and emotion recognition remained. A recent study using simultaneous measurements of fMRI and HRV tested links between resting HRV indexed by SDNN (standard deviation of interbeat intervals) and neural response to emotional faces (Miller, Xia, & Hastings, 2019). It showed that the higher HRV correlated with less activities in the mirror neuron system, insula and amygdala. Therefore, HRV is considered to be related to brain activations in the mentalising network, which is involved in emotion recognition.

SCR has been used to measure ANS responses to emotional stimuli from earlier studies before 2010. For example, negative (fear, sad) emotional stimuli elicited a larger SCR than positive (happy) emotional stimuli (Baumgartner, Esslen, & Jäncke, 2006). Studies have reported that both positive and negative stimuli were associated with greater SCR than neutral stimuli (Lane et al., 1997; Cuthbert et al., 2000), however, SCR is known for its high sensitivity to negative stimuli. A simultaneous fMRI and skin conductance recording has shown that SCR was increased to fearful faces than to neutral faces, and the amygdala activations strongly correlated with SCR (Williams et al., 2001). In addition, SCR and amygdala activations are elicited by subliminally presented emotional stimuli (Gläscher & Adolphs, 2003). A recent systematic review paper indicated that the effects of emotional stimuli on physiological states were most pronounced in fear-related studies measuring SCR (van der Ploeg et al., 2017).

While the SCR appears biased to fear-related stimuli, pupil dilation has been suggested as an index of valence intensity. Bradley and colleagues (Bradley et al., 2008) measured pupil diameter during viewing emotional pictures. The results showed that the pupil diameter was larger during watching pleasant and unpleasant stimuli than neutral stimuli. Pupil dilation during emotion processing can be observed in the process of auditory stimuli in addition to visual stimuli. Oliva & Anikin (2018) showed that human nonverbal vocalisations (e.g. laughing, crying) induced pupil dilation irrespective of whether they were perceived as expressing positive or negative emotional states. Therefore, pupil dilation may reflect the process of valence in emotional pictures irrespective of the type of emotion.

Stress. Another psychological state indexed by ANS measurements is stress. In laboratory settings, acute stress has been induced by various tasks (Bali & Jaggi, 2015). The Trier Social Stress Test (TSST) is one of the most popular methods of inducing acute stress in experimental settings (Allen et al., 2014). The TSST consists of an interview-style presentation and a surprise mental arithmetic test. Cognitive tasks such as Stroop, mirror tracking and mental arithmetic tasks have been used as stressors (Steptoe, Hamer, & Chida, 2007). In addition, the cold pressor, requiring participants to place their hands into a container with cold water (0–3℃), is another manipulation of stress.

ANS responses to stress are generally consistent across measurements, increasing sympathetic activations. From the early physiological study on stress, HR and SC have been correlated with psychological stress (Lazarus, Speisman, & Mordkoff, 1963).

The experimental stressors increase HR (Henckens et al., 2009) and SCL (Jezova et al., 2004; Pisanski et al., 2018). Although acute stress has been shown to induce pupil dilation (Pedrotti et al., 2013), studies measuring pupil dilation remain poorly examined because of the characteristics of the stressors (de Witte et al., 2020). A meta-analysis has shown that resting HRV is also correlated with psychological stress (Thayer et al., 2012). For example, work stress is partly mediated by increased heart rate reactivity to a stressful workday (Vrijkotte, Van Doornen, & De Geus, 2000) and cognitive task increases LF/HF in HRV (Hjortskov et al., 2004). In addition, in a clinical study, patients with stress disorder indicated higher baseline HR and higher LF/HF ratio in the frequency domain during resting (Agorastos et al., 2013). A recent meta-analysis has also suggested that the most frequently reported HRV variable associated with stress is a decrease in HF-HRV and an increase in LF-HRV (Kim et al., 2018).

HR and SCL can be continuously measured throughout testing, including during the stressor. However, participants must avoid movement artefacts during the HR and SCL measurements. Thus, salivary cortisol has been used in many stress-related studies. Cortisol is considered the major stress hormone in humans (Lupien et al., 2007). Cortisol levels are controlled by the hypothalamic-pituitary-adrenal axis which is the major endocrine stress axis of the human organism (Hellhammer, Wüst, & Kudielka, 2009). Kidd, Carvalho, & Steptoe (2014) tested associations between cortisol responses to a set of laboratory stressors (colour/word interference and mirror tracing) and cortisol output throughout the day. It was shown that cortisol responses to acute stress in laboratory settings were positively associated with cortisol output over the day independently of sex, age, socioeconomic status, smoking, body mass index and time of laboratory testing.

Reward. HR and SCR are believed to be related to the reward perception reflecting implicit liking and wanting of a stimulus (Kuoppa et al., 2016; Cecchetto et al., 2022). An early study indicated that HR increased when participants were paid a monetary reward for each success feedback compared to participants who received feedback only (Fowles, Fisher, Tranel, 1982). Heart rate linearly increases with levels of monetary reward (Brinkmann & Franzen, 2013). Furthermore, a recent study has reported that HR correlates with the amount of incentive values, more incentive values induce higher HR (Silvia et al., 2019). SCR is also enhanced when receiving a monetary reward (Zink et al., 2004; Choi et al., 2014). In addition, SCR increases also reflect reward-related psychological states such as alcohol and cigarette cravings (Nees et al., 2012; LaRowe et al., 2007).

In addition, eye measures can index the reward process. It has been suggested that reward-related striatal dopamine activity is correlated with increases in pupil dilation and eye blinks, thus these eye measures can index activations in the reward system (Eckstein et al., 2017). Pupil dilation can be observed during watching a rewarding stimulus and while watching a reward-predictive stimulus (Anderson & Yantis, 2012; O’Doherty et al., 2006). Furthermore, pupil dilation predicts expected action values, which are the outcomes of reward-based action choices (Ishikawa & Itakura, 2022). Eye blinks are strongly linked to dopamine activity in the brain. Primate studies have suggested that eye blinks positively correlate with dopamine receptors availability in the striatum (Groman et al., 2014). The number of eye blinks is a predictor of dopaminergic activity and reward maximisation during decision-making (Barkley-Levenson & Galvan, 2016). Increases in the EBR can be observed from infancy about 7-month-olds while observing a socially rewarding stimulus (e.g. mother; Tummeltshammer, Feldman, & Amso, 2019).

These studies compared ANS responses between the reward gain and the no-reward condition. However, ANS responses have been observed to have a higher sensitivity to punishment rather than reward gain. Studies directly comparing responses to reward and punishment have found greater responses, as measured by HR, SCR and pupil diameter, to monetary losses in comparison to gains (Hochman & Yechiam, 2011; Yechiam & Telpaz, 2011; van't Wout et al., 2006).

Complexities of ANS indexes

In the previous section, a brief overview of the use of ANS measures in each research topic was provided. Also, the results of the recent meta-analyses have been included if applicable. However, psychological research using ANS measures sometimes yields inconsistent results. This section refers to the complexities of ANS indexes that contribute to such inconsistencies in psychological research.

Interactions between cognitive and affective processes. Firstly, each of the research categories summarised in the previous section interacts with each other. It was simplified to provide an overview how ANS measures are used in psychophysiology. However, ANS activities can be affected by multiple psychological processes at the same time. For example, during the reward presentation, physiological states are increased, which is assumed as a cognitive process of reward (e.g. reinforcement learning). While the enhanced physiological states during the reward presentation possibly include positive valence, which is an affective process. Similarly, physiological measures of attention to emotional stimuli include a cognitive aspect of attentional control and an affective aspect of emotional stimuli. ANS activities could be induced as outcomes of interactions between cognitive and affective processes. Thus, interpretations of ANS activities should be carefully considering what psychological processes can be included.

Tonic and phasic changes. Secondly, the differences between tonic and phasic levels of ANS activities should be considered. Tonic activation refers to shifts in the overall baseline of activity such as SCL and baseline pupil size, whereas phasic activity refers to fluctuations occurring in response to an event such as SCR and task-evoked pupil responses (Wass et al., 2015). Neuroimaging studies have shown differences in the neural correlates between tonic and phasic activities (for more details on neural mechanisms please see Mathôt, 2018: pupil; Zhang et al., 2014: SC). In psychological studies, it has been shown that tonic and phasic ANS activities are differentially related to cognitive processes. For example, Howells et al. (2010) investigated how tonic or phasic SC and HR correlate with mental efforts during attentional tasks. The results showed that increases in SCL and HR were seen from rest to completion of the attentional tasks and between the attentional tasks rather than responses to each trial. These results indicate that mental effort for information processing is reflected in tonic rather than phasic changes in the ANS activities during the tasks of attention. More recently, tonic and phasic pupil sizes were measured before and during multiple object tracking to investigate correlations between pupil responses and cognitive load (Aminihajibashi et al., 2020). They found no correlations between tonic pupil sizes and cognitive load, however, participants with high performance in the highest cognitive load condition showed larger phasic pupil responses, suggesting increases in phasic pupil responses reflect the high cognitive load. Tonic and phasic changes in ANS activities have different correlations with psychological processes.

In addition, within the phasic changes, time scales of effects on ANS activities could affect inconsistent results of psychophysiological research. For example, as introduced in the above section, some studies have shown increases in HR associated with attention levels, while other studies have shown decreases in HR associated with attention. Although the ANS activities depend on which function of attention is measured, these controversial results would be observed because of the phasic changes. As illustrated in Figure 1, both sympathetic and parasympathetic nervous systems modulate responses in each index. The activation of the parasympathetic nervous system decreases HR and this effect is mediated by the neurotransmitter acetylcholine, whereas the activation of the sympathetic nervous system increases HR and this effect is mediated by the neurotransmitter noradrenaline (Berntson et al., 2017). It has been shown that acetylcholine affects HR faster than noradrenaline, thus the decrease in HR is observed earlier than the increase in heart rate due to the activity of the sympathetic nervous system. In empirical studies, it has been observed that immediate HR deceleration (after exposure to an emotional stimulus) and HR acceleration following the initial HR deceleration (Bradley et al., 2001; Osumi & Ohira, 2016). The time scale of changes in ANS activities should be considered.

Pros and Cons of ANS measurements

ANS measurements have been widely used in psychological studies and have contributed to understanding the biological mechanisms of human cognition.

First, ANS measurements are easier and cheaper than neuroimaging but it is possible to suggest neurophysiological mechanisms. Using an fMRI requires technicians, expensive running costs and long testing periods. Functional near-infrared spectroscopy (fNIRS) is considered an easier brain imaging technique than fMRI. However, the fNIRS can only measure from regions near the cortical surface. In contrast, ANS measurements are easier to obtain when recording data, HR and SC can be measured after putting electrodes on the proper position, and pupil diameter and eye blinks can be measured during running an eye tracker after short calibrations. Neural correlates of ANS activities have been reported. For example, HRV is controlled by the central autonomic network including brain regions of the prefrontal cortex, anterior cingulate cortex, insula, amygdala, periaqueductal grey, pons and medulla (Mulcahy et al., 2019). Also, Pupil dilations are modulated by the activity of the noradrenergic system’s locus coeruleus, suppling NA to the cortex, cerebellum, and hippocampus (Wilhelm et al., 1999). Thus, ANS measurements cannot directly investigate brain activations, but it is possible to use them with hypotheses based on mechanisms suggested in neuroimaging studies.

Furthermore, ANS measurements can be used in a wide range of situations or tasks. In brain imaging studies, due to the high impact of artefacts such as body movements and speech, tasks are quite limited. Social neuroscience is one of the core topics in cognitive neuroscience, however, brain imaging studies in social neuroscience have been criticised for their lack of ecological validity, as participants do not engage in real interaction (Schilbach et al. 2013). On the other hand, ANS measurements have been known for their utility in situations with high ecological validity (Hoehl, Fairhurst, & Schirmer, 2020). For example, to investigate emotion regulation in real interaction, Wass et al. (2019) measured HR, HRV, and movement in infants and parents concurrently in naturalistic settings. Also, SCL has been used to measure acute stress during an interview-style oral presentation included in the TSST (Montero-López et al., 2016). Thus, ANS measurements have advantages in naturalistic situations including physical activity and real interaction compared to brain imaging techniques.

Since ANS activities can be easily measured, it is possible to include a variety of populations. Although there are some fMRI studies in awake infants, it is difficult to have infants conduct cognitive tasks in the fMRI (Yates, Ellis, & Turk-Browne, 2021). Eye-tracking has been used widely in developmental studies, and the eye tracker records pupil diameter to capture eye areas, which can be used more to investigate infants’ cognitive processing (Eckstein et al, 2017). Because ANS measurements are relatively easier to measure than brain measurements, they are easier to investigate on a large scale.

In addition, the devices are more affordable than fNIRS and EEG systems. Studies simultaneously using fMRI and ANS measurements have highlighted correlations between specific brain areas and ANS responses during cognitive tasks (e.g. Napadow et al., 2008; Schneider et al., 2018). Therefore it is possible to discuss neurophysiological mechanisms of cognitive processing by using ANS measures. This is especially beneficial for students and early career researchers who cannot afford brain imaging techniques.

Another characteristic is that ANS measurements have different temporal resolutions. Therefore, researchers can choose a measurement appropriate to their research objectives. For example, in extreme cases, pupil dilation can index event-related ANS responses in several seconds, while HR and HRV can be measured throughout the entire day. Because of this flexibility in the temporal scale, ANS measurements such as HRV can also be applied in the evaluation of stress and psychiatric disorders (Kim et al., 2018). Researchers need to consider the time resolution required for the cognitive processing they aim to investigate.

However, ANS measurements cannot directly investigate neural mechanisms of cognitive processing. An fMRI study has shown that smiling faces enhance activation in the ventral striatum, a core region of the reward system, whereas angry faces increase activation in the amygdala processing emotion and threatening information (Vrtička et al., 2008). This suggests the different cognitive processing of each emotional face respectively. However, in a passive viewing paradigm measuring pupil diameter, it is predicted that pupil dilation can be observed while observing smiling and angry faces because pupil diameter increases while watching pleasant and unpleasant stimuli (Bradley et al., 2008). Measuring ANS responses in cognitive tasks may have this problem of interpretation. Also, ANS measures have been mainly used to investigate relations with psychological states/processes. However, as discussed in Complexity of ANS indexes, the results of psychophysiological studies using ANS measures are inconsistent sometimes. Thus, it is essential to combine other indexes to identify which psychological aspects affect ANS activities. For example, behavioural measurements in reward learning tasks requiring to participants learn associations between cues and outcomes can be applied to investigate reward-related pupil dilations (Tummeltshammer et al., 2019; Schneider et al., 2020). Also, many brain regions have been defined by each function in neuroimaging (Genon et al., 2018), thus simultaneous measurements of ANS and brain activations could contribute to the identification of psychological functions. In psychophysiological studies using ANS measures, designing experiments focusing on specific processing is essential and combining other indexes would be helpful to identify psychological factors.

In addition, ANS measures can be used in broader situations than neuroimaging, they are affected by variables such as temperature, luminance, and loudness during recording. For example, lighting affects levels of HR and SC (Smolders & de Kort, 2017) and modulations of air temperature on ANS states have been shown to be associated with cognitive processing such as emotional evaluation (Barbosa Escobar et al., 2021). Consequently, researchers should ensure the similarity of the testing environment across participants and report information on room brightness and temperature.

By designing experiments with these points in mind, ANS measures can be useful in psychological research. The ANS measures can provide data that are objective and can be described as physical quantities such as voltage or frequency. Also, the process by which psychological activity occurs can be analysed along the time course of ANS activities change. Some of the ANS measures can detect unconscious physiological responses such as SCR to subliminally presented stimuli (Gläscher & Adolphs, 2003). Also, these measurements can be used for sleep research (Laborde et al., 2017). By making use of these features, the ANS measurements can be applied to a wide range of psychological research which may contribute to investigating neurophysiological mechanisms of psychological processes. In addition, ANS measures could be used as a biomarker in health and affective disorders. For example, cardiac dysregulation can be observed in clinical states that include affective disorders (for a review see Mulcahy et al., 2019). HF-HRV suppression is observed in mood disorders (Alvares et al., 2016), depression (Sgoifo et al., 2015), and anxiety (Makovac et al., 2016), suggesting that HRV can be used as a biomarker for autonomic dysregulation in clinical conditions. Similarly, it has been suggested that pupil dilation can be used as a biomarker for sleep disorders, seasonal affective disorders, and also Alzheimer's disease (Zele & Gamlin, 2020). Because ANS activities can be easily measured and have a strong association with the central nervous system, they can be applied to support diagnosis in clinical situations.

Conclusion

Physiological measures in psychology primarily index activations in the ANS, consisting of sympathetic and parasympathetic nerve activations. HR, SC and eye measures have been used in a variety of psychophysiological studies and these measurements have different characteristics. These data can be more easily collected than the neuroimaging techniques, and correlations between ANS responses and activations in specific brain areas have been shown in fMRI studies. However, ANS measures are affected by various environmental factors. Also, increases or decreases in each index measuring ANS activities can be induced by multiple psychological processes. It is important to design experiments so that it is possible to identify which psychological state or cognitive processing is associated with the measured ANS activities.

To clarify the interpretation of ANS activities, it is necessary to design experiments which are effective for each measurement and use other index types such as behavioural measurements. Ayres et al. (2021) conducted a meta-analysis with a sample of 33 experiments that used ANS measures to measure cognitive load. Their objective was to test the validity of ANS measures indexing cognitive load. They showed that pupil diameter and eye blinks are the most sensitive followed by the HR and lungs, SC and brain activities. However, subjective measures of cognitive load by self-rating had the highest levels of validity. Therefore, a combination of ANS and subjective measures is suggested to be most effective in detecting changes in cognitive load. Thus, psychophysiological research should measure subjective and/or behavioural measures simultaneously. Coles (1989) described psychophysiological measures are 'windows on the mind' and 'windows on the brain'. Therefore, by using well-designed experiments and creating proper paradigms, ANS measurements contribute to our understanding of psychological states and cognition.

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Table 1. Studies measuring heart rate cited in this paper.

Study	Measure	Main factor	Correlation with main factor
Wass et al. (2016)	HR	Visual attention duration	HR increase
de Barbaro et al. (2017)	HR	Vigilant visual attention	HR increase
Petrie et al. (2012)	HR	Attention focus	HR decrease
Tonnsen et al. (2018)	HR	Sustained attention	HR decrease
Cobos et al. (2019)	HR	Perceptual sensitivity	HR decrease
Siennicka et al. (2019)	Resting HRV	Attention control	Higher HRV
Park et al. (2012)	Resting HRV	Attention to fearful face cues	Higher HRV
Park et al. (2013a)	Resting HRV	Attention maintenance	Higher HRV
Park et al. (2013b)	Resting HRV	Attention maintenance	Higher HRV
Barber et al. (2020)	HR	Attention maintenance	HR decrease
Chang & Huang (2012)	Task-related LF-HRV	Attention levels	LF-HRV decrease
Quintan et al. (2012)	Resting HF-HRV	Emotion recognition	HF-HRV increase
Miller et al. (2019)	Resting HRV	Neural response to emotional faces	Lower HRV
Lazarus et al. (1963)	HR	Acute stress	HR increase
Henckens et al. (2009)	HR	Acute stress	HR increase
Vrijkotte et al. (2000)	Long-term HRV	Work stress	Higher HRV
Hjortskov et al. (2004)	HR & LF/HF ratio	Cognitive stress	HR increase & higher LF/HF ratio
Agorastos et al. (2013)	LF/HF ratio	Stress disorder	Higher HR & higher LF/HF ratio
Kuoppa et al. (2016)	Task-related HRV	Food reward	HRV increase
Fowles et al. (1982)	HR	Monetary reward	HR increase
Brinkmann & Franzen (2013)	HR	Monetary reward	HR increase
Silvia et al. (2019)	HR	Monetary reward	HR increase
Hochman & Yechiam (2011)	HR	Monetary loss	HR increase

Note. HR = Heart rate is usually calculated by the standard measure of beats per minute (bpm), averaged heart rate in a specific period.

HRV = Heart rate variability is defined as the beat-to-beat variation in heart rate.

LF = Low-frequency is a frequency domain index of HRV, influenced by both sympathetic and parasympathetic activity.

HF = High-frequency is a frequency domain index of HRV, usually considered as a measure of parasympathetic activity.

Table 2. Studies measuring skin conductance cited in this paper.

Study	Measure	Main factor	Correlation with main factor
Frith & Allen (1983)	SCR	Attention during cognitive task	SCR increase
Codispoti & De Cesarei (2007)	SCR	Visual attention	SCR increase
Baumgartner et al. (2006)	SCR	Emotional stimuli	SCR increase
Lane et al. (1997)	SCR	Emotional stimuli	SCR increase
Cuthbert et al. (2000)	SCR	Emotional stimuli	SCR increase
Williams et al. (2001)	SCR	Emotional faces	SCR increase
Gläscher & Adolphs (2003)	SCR	Subliminal emotional stimuli	SCR increase
Lazarus et al. (1963)	SCR	Acute stress	SCR increase
Jezova et al. (2004)	SCL	Social stress	Higher SCL
Montero-López et al. (2016)	SCL	Social stress	Higher SCL
Cecchetto et al. (2022)	SCR	Food reward	SCR increase
Zink et al. (2004)	SCR	Monetary reward	SCR increase
Choi et al. (2014)	SCR	Monetary reward	SCR increase
Nees et al. (2012)	SCR	Alcohol craving	SCR increase
LaRowe et al. (2007)	SCR	Cigarette craving	SCR increase
van'tWout et al. (2006)	SCR	Monetary loss	SCR increase

Note. SCR = Skin conductance response is a phasic, usually elicited by an event, increase in skin conductance.

SCL = Skin conductance level is a tonic level of conductance or resistance

Table 3. Studies measuring eyes cited in this paper.

Study	Measure	Main factor	Correlation with main factor
Smallwood et al. (2011)	PD	Attentional effort	PD increase
Kang et al. (2014)	PD	Attentional effort	PD increase
Irons et al. (2017)	PD	Attention control	PD increase
Willems et al. (2015)	PD	Predictive attention control	PD increase
Granholm et al. (1996)	PD	Cognitive load	PD increase
Klingner et al. (2011)	PD	Cognitive load	PD increase
Ohira (1996)	EBR	Cognitive load	Higher EBR
Ichikawa & Ohira (2004)	EBR	Information processing	Higher EBR
Magliacano (2020)	EBR	Cognitive load	Higher EBR
Siegel et al. (2008)	EBR	Information processing	Higher EBR
Oh et al. (2012)	EBR	Task difficulty	Lower EBR
Maffei & Angrilli (2018)	EBR	Attentional load	Lower EBR
Hoppe et al. (2018)	EBR	Task-related cost	Lower EBR
Ranti et al. (2020)	EBR	Task engagement	Lowe EBR
Bradley et al. (2008)	PD	Emotional stimuli	PD increase
Oliva & Anikin (2018)	PD	Nonverbal vocalisations	PD increase
Pedrotti et al. (2013)	PD	Cognitive stress	PD increase
Anderson & Yantis (2012)	PD	Monetary reward	PD increase
O'Doherty et al. (2006)	PD	Food Reward	PD increase
Ishikawa & Itakura (2022)	PD	Expected reward value	PD increase
Barkley-Levenson & Galvan (2016)	EBR	Reward prediction	Higher EBR
Tummeltshammer et al. (2019)	EBR	Social reward	Higher EBR
Hochman & Yechiam (2011)	PD	Monetary loss	PD increase
Yechiam & Telpaz (2011)	PD	Monetary loss	PD increase

Note. PD = Pupil diameter is usually compared between the baseline and evoked changes in pupil size.

EBR = Eye blink rate is an average number of blinks per minute which is reflective of cognitive factors such as attention and reward processing.